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NASA Contractor Report 3060

Helicopter Mission Optimization Study

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Helicopter Mission Optimization Study

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FOREWORD

Sikorsky Aircraft, a Division of United Technologies Corporation, has developed programs for use in a hand-held computer that enable a CH-53 helicopter pilot to determine optimum flight conditions for minimization of fuel consumption or takeoff and landing noise. The work was accomplished under contract NAS1-14980 for the National Aeronautics and Space Administration during the period from July, 1977 to June, 1978.

A portable, programmable, printing calculator with magnetic card inputs of the developed programs was delivered, with this report, in fulfillment of the contract.

NASA technical representatives were Mr. Jerry Keyser and Mr. William Snyder. The author acknowledges the special efforts of Sikorsky engineers Phillip Gold, who was responsible for the programming and user documentation, and Larry Levine and Anthony Belloli, who performed the takeoff and landing noise analyses.

SUMMARY

The objective of this project was to take advantage of currently available, low-cost computer technology to demonstrate the feasibility of providing the helicopter pilot with onboard capability to rapidly establish optimum flight conditions for minimization of fuel consumption or takeoff and landing noise. Programs for this purpose were developed specifically for the CH-53 helicopter and the Hewlett Packard HP-97 calculator, but the concepts have general application.

Eight individual programs were developed, this number being the best compromise between the handling convenience of few and the accuracy and input/output simplicity of many. These programs determine: (1) power required, (2) fuel flow, (3) best range conditions, (4) best range performance, (5) best endurance conditions and performance, (6) maximum sustained speed, (7) minimum noise takeoff conditions, and (8) minimum noise landing conditions.

Typical program inputs are gross weight, temperature, and wind. Typical outputs are optimum airspeed, optimum altitude, optimum rotor rpm, and the corresponding optimized performance.

Up to fifty percent fuel savings can be achieved by operating at optimum flight conditions, the exact saving depending on the initial, non-optimum conditions and on applicable flight envelope restrictions. Most of this saving is due to altitude and airspeed optimization, with up to 5% contributed by optimizing rotor rpm.

Takeoff noise is minimized by climbing at low rotor rpm and maximum achievable climb angle. Landing noise is minimized in autorotation at low rotor rpm and a descent angle of about eleven degrees. Noise reductions of 10 dB EPNL can be realized compared to typical non-optimum climb and descent procedures.

Optimum flight conditions are defined without constraining them by CH-53 flight envelope restrictions. This approach was taken in order not to penalize performance potential by constraints that may change or that may not apply in selected situations. The impact of current CH-53 flight envelope restrictions is discussed.

LIST OF FIGURES

LIST OF SYMBOLS

ALT	Pressure altitude
A/S	Airspeed
c	Speed of sound
CAS	Calibrated airspeed
C_P	Main rotor power coefficient, SHP x 550/(disc area x ρ x tip speed^3)
C_W	Weight coefficient, GW/(disc area x ρ x tip speed^2)
EPNL	Effective Perceived Noise Level, decibels
FF	Fuel flow
GW	Gross weight
hp	Pressure altitude
H WIND	Headwind speed
H_z	Hertz frequency, cycles per second
IAS	Indicated airspeed
ISA	International Standard Atmosphere
k_{as}	Airspeed fuel flow correction
k_c	Compressibility power correction
k_{st}	Stall constant
k_{tr}	Tail rotor power correction
M_t	Advancing blade tip Mach number
NE	Number of engines operating
N_R	Rotor speed, percent (100% = 185 main rotor rpm)
OAT	Outside ambient temperature
OPT	Optimum
PNL	Perceived Noise Level, decibels
Q	Engine Output Torque, percent (100% = 3200 SHP per engine at 100% N_R)
R	Rotor radius
ROC	Rate of climb
ROD	Rate of descent
SHP	Total engine shaft horsepower
SPE	Specific endurance, time per unit fuel weight
SPR	Specific range, distance per unit fuel weight
STD	International standard atmosphere (ISA)

T	Outside ambient temperature (OAT)
TAS	True airspeed
V_{max}	Maximum sustained airspeed
V_{pwr}	Power-limited airspeed
V_{red}	Red-line structurally-limited airspeed
V_{st}	Stall-limited airspeed
V_{WIND}	Wind speed
ρ	Mass density of air
ρ_o	Mass density of air at sea level ISA
μ	Rotor advance ratio, true airspeed/rotor tip speed
ΩR	Rotor tip speed
γ	Climb or descent angle

INTRODUCTION

As the helicopter continues to mature into an important element of the world transportation system, it faces increasing demands for safety, economy, energy conservation, and public acceptance. The National Aeronautics and Space Administration has responded to these demands with an aggressive Civil Helicopter Technology Program that has sponsored research in the areas of passenger acceptance, noise and vibration reduction, gust suppression, fuel conservation, improved handling qualities, and air traffic control.

The Helicopter Mission Optimization Study described in this report is a part of the NASA Civil Helicopter Technology Program. Its objective is to demonstrate the feasibility of using low-cost, portable computer technology to help a helicopter pilot optimize flight parameters to minimize fuel consumption and takeoff and landing noise.

The wide operating envelope of the helicopter makes it particularly sensitive to flight optimization. This envelope includes a speed range down to zero and the variable of rotor rpm, neither of which is available to the fixed wing aircraft.

The benefits achievable from optimizing helicopter flight parameters are significant and relatively easy to identify. The more difficult problem is how best to put flight optimization into practice. Methods for doing so range from providing the pilot with charts of the type found in flight manuals, to the ultimate of a full autopilot that senses ambient conditions and automatically adjusts flight controls to achieve a specified optimization goal. Neither of these extremes is practical, the former because continual in-flight reference to a volume of charts is awkward, the latter because low-cost automatic systems are not currently available nor compatible with present piloting or air traffic control procedures.

The approach taken in this study is a cost-effective compromise between these two extremes. The pilot flies the helicopter and is provided with onboard capability to quickly determine optimum flight parameters based on a few, readily available inputs to a small, portable computer.

CONCEPTUAL PROGRAM DESIGN

Consistent with the objective of enabling the pilot to rapidly establish and implement optimum flight conditions, program operation is kept as simple and straightforward as possible. Inputs and outputs are limited to those with a significant effect on performance. Inputs are readily available to the pilot and outputs are easily put into practice. The resulting program logic is shown in Figure 1.

Primary inputs are the desired optimization goal, gross weight, air temperature, and wind. Primary outputs are pressure altitude, airspeed, rotor rpm, and corresponding performance. Constraints can be imposed by specifying one or more of the primary outputs as inputs. For example, pressure altitude may not be an available option due to air traffic control restrictions. All inputs are available to the pilot, from pre-flight information, instrument observations, or communication with ground control.

Center of gravity was not included as an input because it has relatively small performance impact (less than 2% on power required - see Assumptions and Limitations) and also because it is not readily determined, particularly as fuel is consumed or payload is redistributed.

Calculations and trending were performed using customary units of measurement. Program inputs and outputs are expressed in customary units rather than SI (metric) units to be compatible with CH-53 instruments and publications. (The figures in this report are plotted with primary scales in SI units and secondary scales in customary units, consistent with NASA report standards.) True and indicated (calibrated) airspeeds are generally provided as alternative inputs, and both are presented when airspeed is an output. Temperature can generally be input either in degrees F or degrees C. Where possible, standard ISA temperature at the specified pressure altitude is automatically provided as an optional input.

The optimization is divided into eight individual programs to simplify input and output while providing acceptable accuracy within the 224-step programming capacity of the Hewlett Packard HP-97. The eight programs are power required, fuel flow, best range conditions, best range performance, best endurance conditions and performance, maximum speed, minimum noise takeoff, and minimum noise landing.

Each program is defined by a maximum of two magnetic cards. After loading in the computer, the title magnetic card is inserted in the face of the computer to label input and output parameters. Inputs are keyed in and the desired output is designated. Keyed-in inputs appear in the display for verification before entry and are recorded on paper tape after entry for future reference. Outputs appear in the display and are also printed out on paper tape.

Program organization and operation is described more fully in the section entitled Detail Program Design and in the appendices.

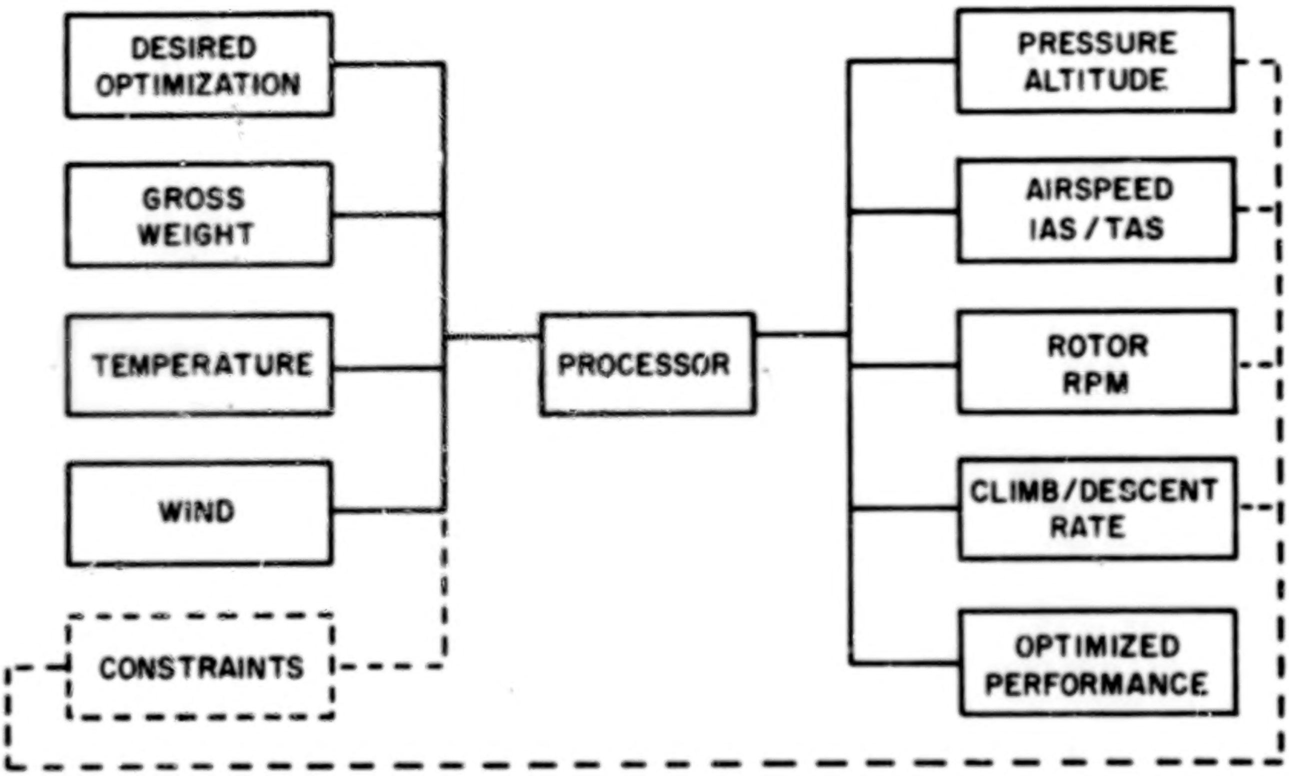


Figure 1. Conceptual Program Design.

PERFORMANCE ANALYSES

This section describes the methodology used to define the following performance characteristics:

Power required
Minimum fuel consumption - range
Minimum fuel consumption - endurance
Maximum speed
Noise methodology
Takeoff noise
Landing noise

Power Required

CH-53 power required is programmed in a non-dimensional format that improves accuracy and reduces the required number of computer steps compared with a dimensional approach. In particular, it facilitates treatment of rotor rpm variation. This format consists of main rotor power coefficient versus advance ratio for a range of weight coefficients (Figure 2). Total power is found by dimensionalizing Figure 2 at the appropriate gross weight, airspeed, rotor rpm, and air density and multiplying the result by the compressibility correction (k_c) of Figure 3 and the tail rotor correction (k_{tr}) of Figure 4. Constant accessory power of 147 hp is added and an overall mechanical efficiency of 99.5% is applied:

$$SHP = (\text{Power from Figure 2} \times k_c \times k_{tr} + 147) \times 1/.995$$

Correlation of the resulting power required with the data used to develop CH-53 flight manual performance is shown in Figures 5 and 6.

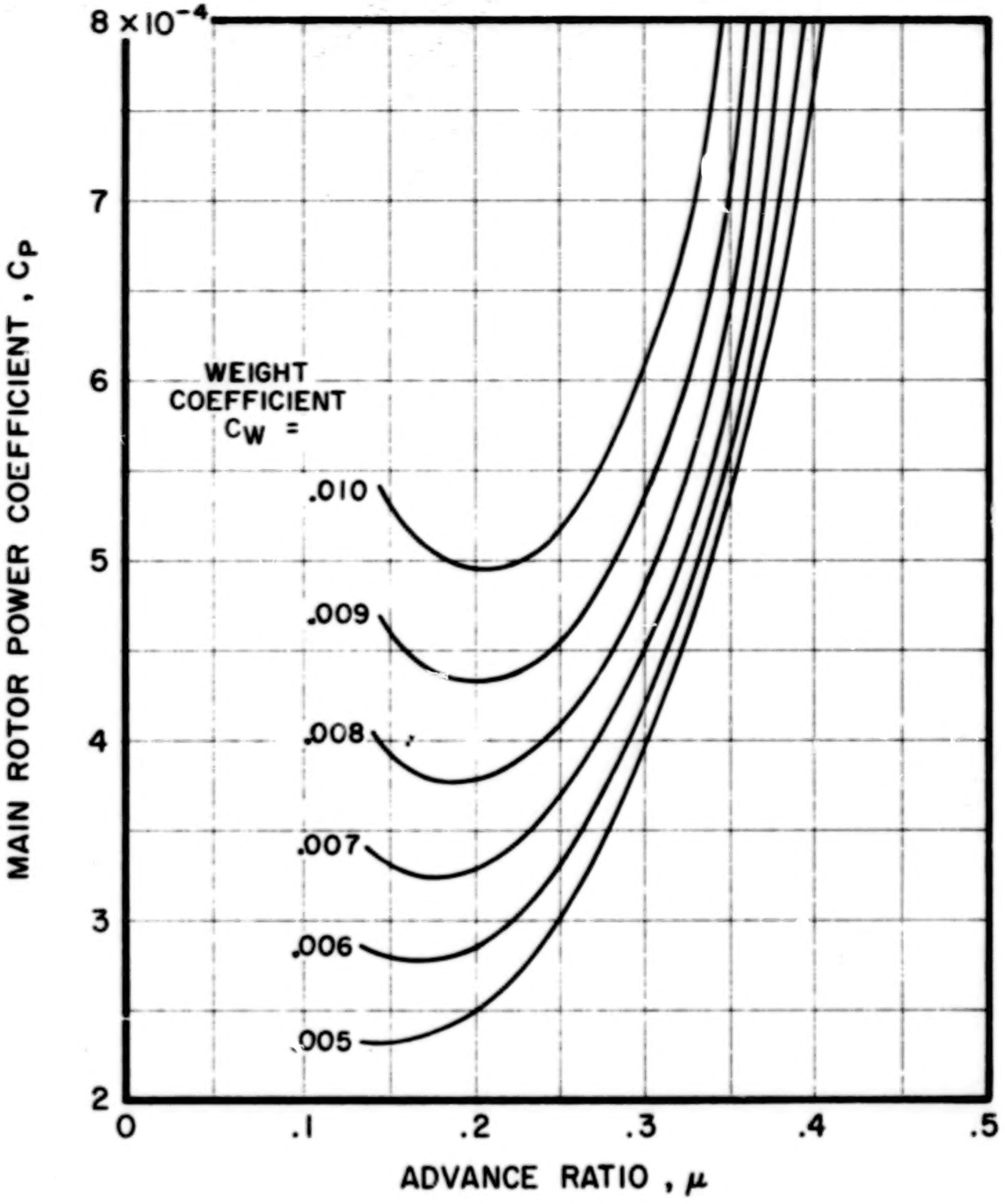


Figure 2. Non-dimensional CH-53D Main Rotor Power Required.

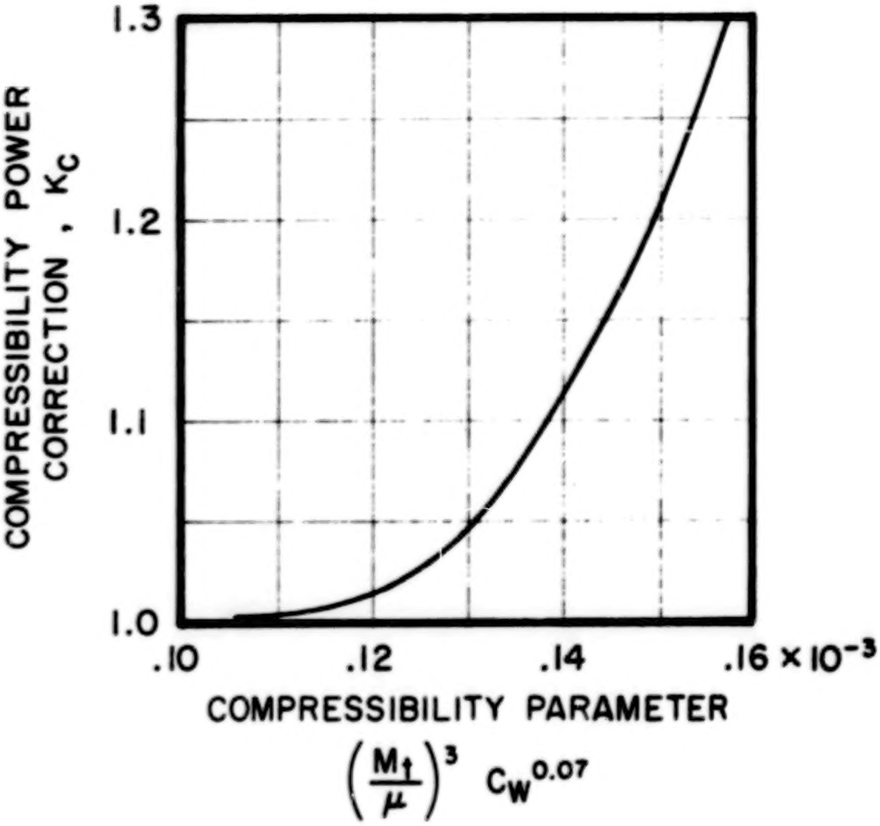


Figure 3. Compressibility Power Correction.

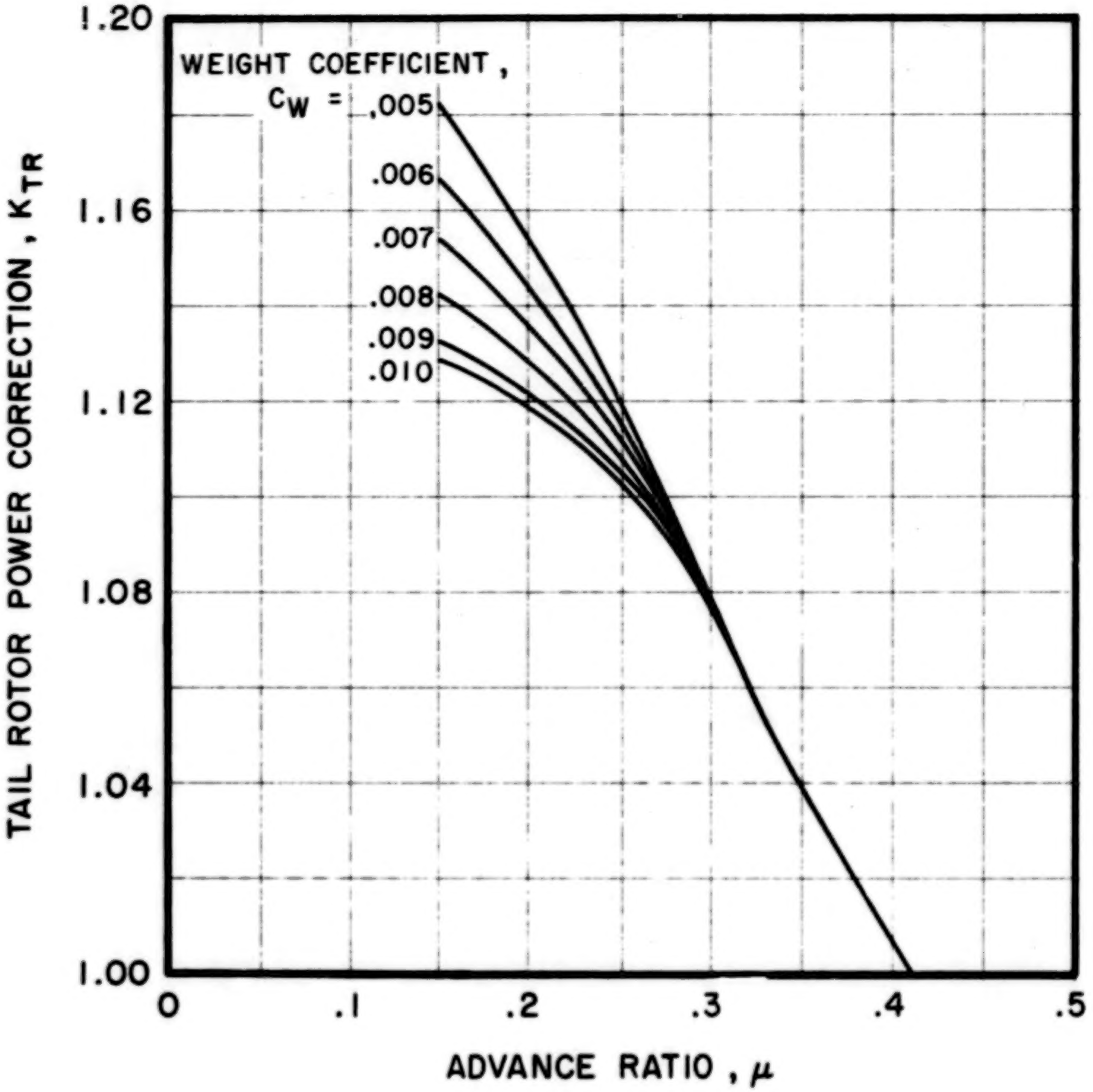


Figure 4. Tail Rotor Power Correction.

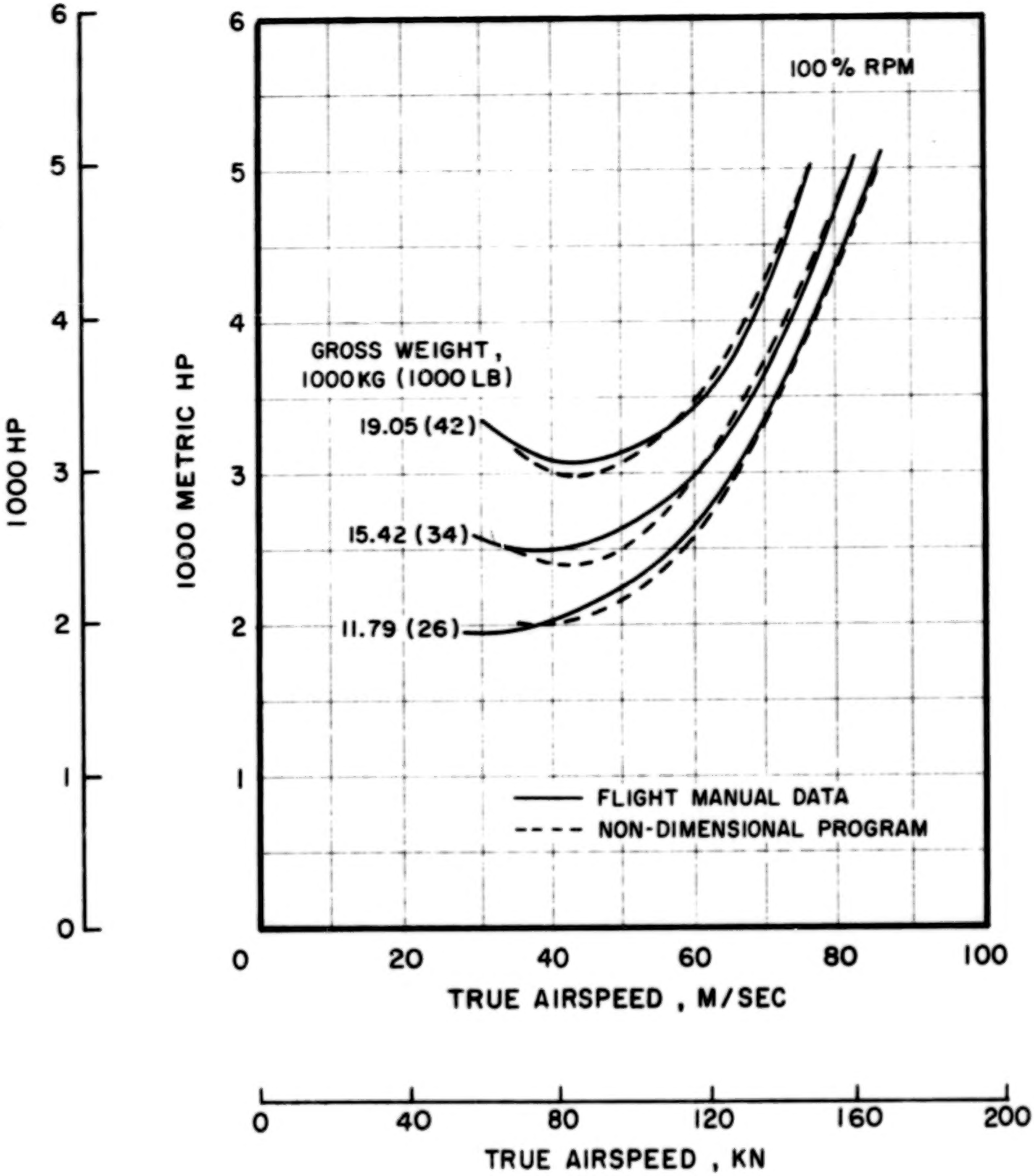


Figure 5. CH-53D Power Required Correlation at Sea Level ISA.

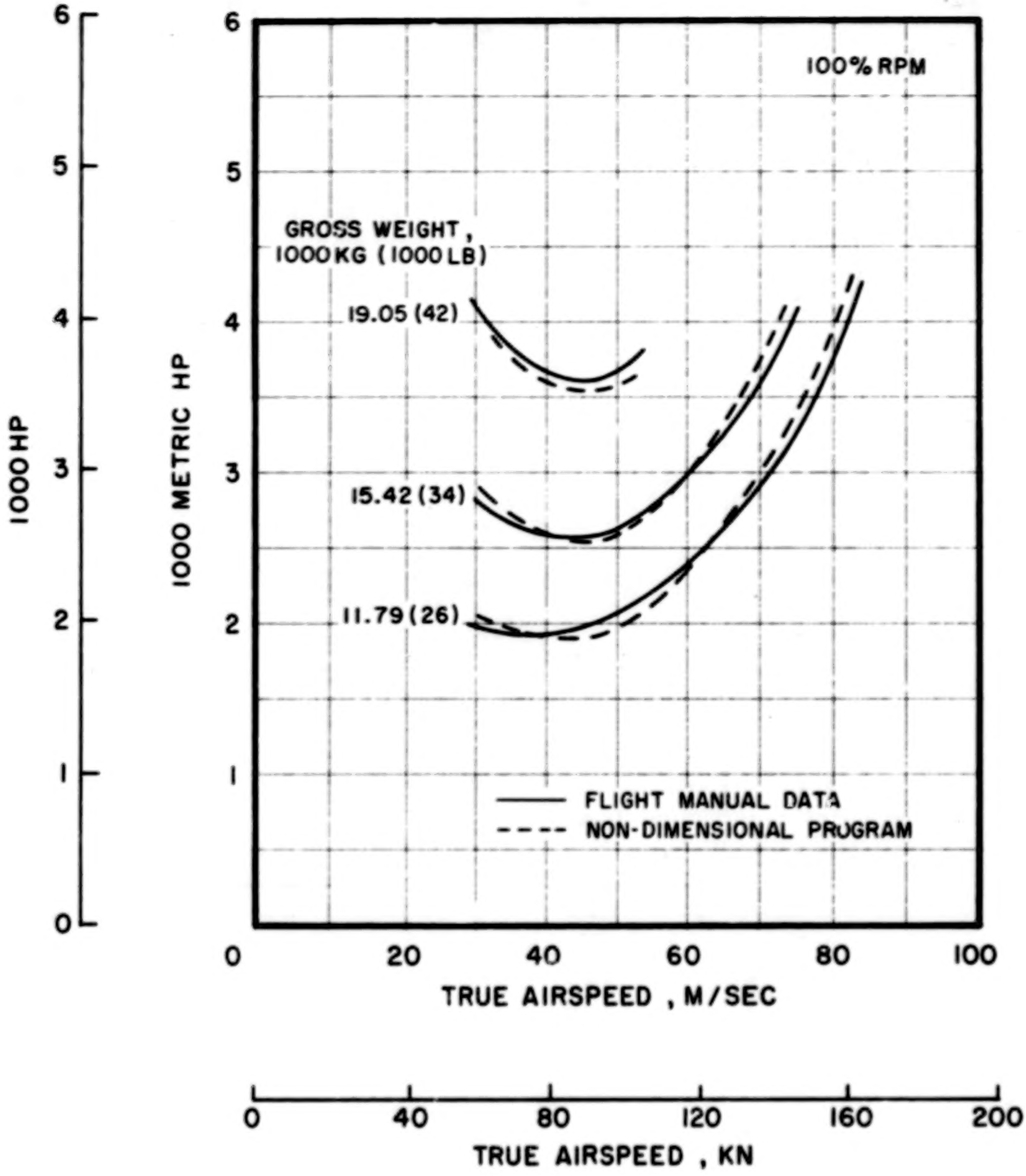


Figure 6. CH-53D Power Required Correlation at 3048m (10000 ft) ISA.

Minimum Fuel Consumption - Range

Flight conditions resulting in minimum fuel consumption for a given range were developed by combining the output of the power required analysis with the engine fuel flow performance illustrated in Figure 7. The trends and relationships thus developed were then programmed using curve-fit techniques.

Specific range was used as the measure of fuel efficiency for a given range. This parameter is equal to unit distance per unit of fuel weight and is expressed as kilometers per kilogram in metric units and nautical miles per pound in customary units.

Specific range sensitivity to airspeed is illustrated in Figure 8 for a range of gross weights and altitudes in zero wind. Optimum true airspeed falls in the range from 66 to 68 m/sec (128 to 132 knots). With a headwind, best range airspeed increases; with a tailwind, it decreases (Figures 9 and 10). As shown in Figures 11 and 12, best range rotor rpm varies from 90 percent or less at low altitude and gross weight to over 100 percent at high altitude and gross weight.

Figure 13 shows the best achievable specific range as a function of gross weight and altitude for zero headwind and ISA temperature.

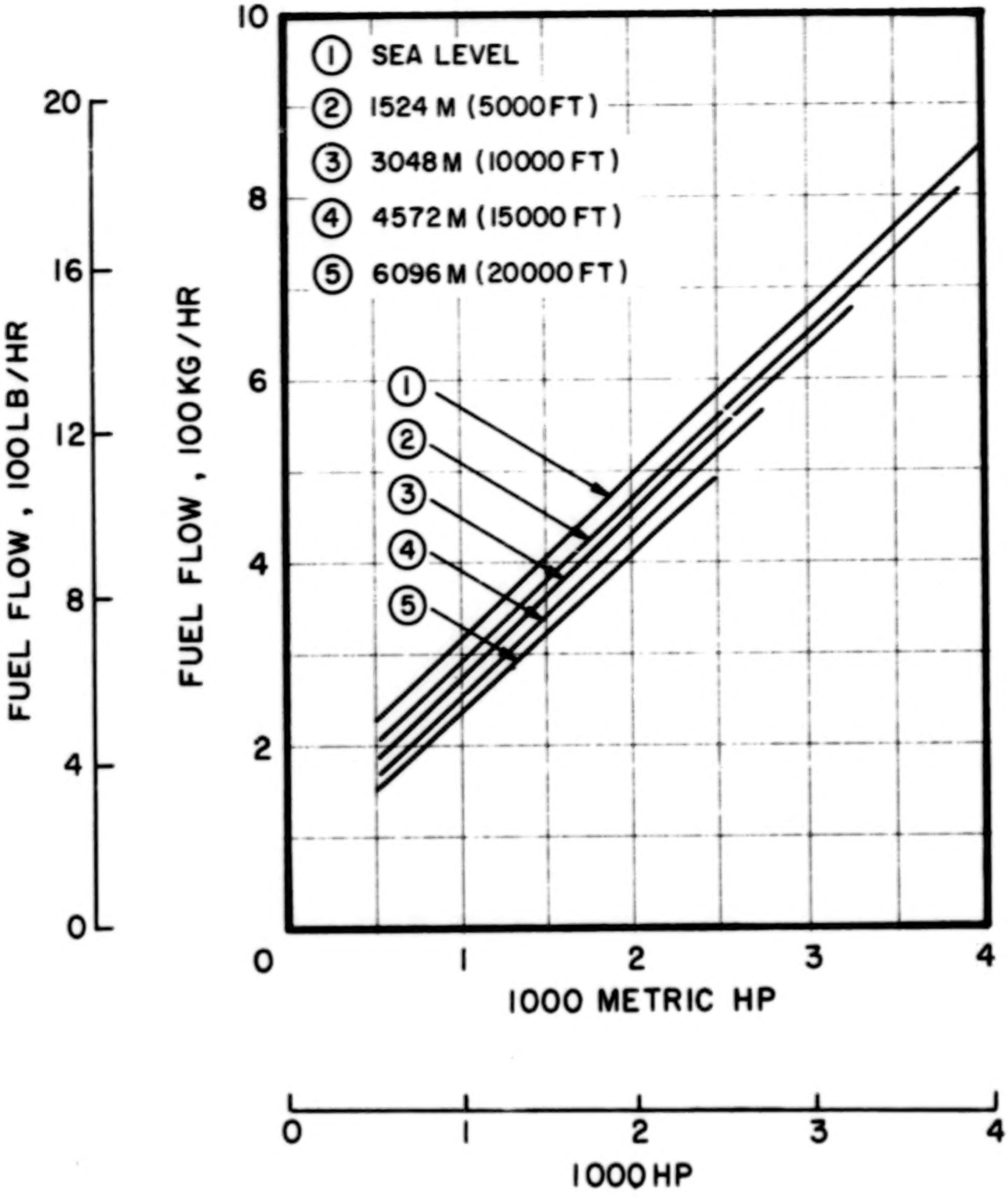
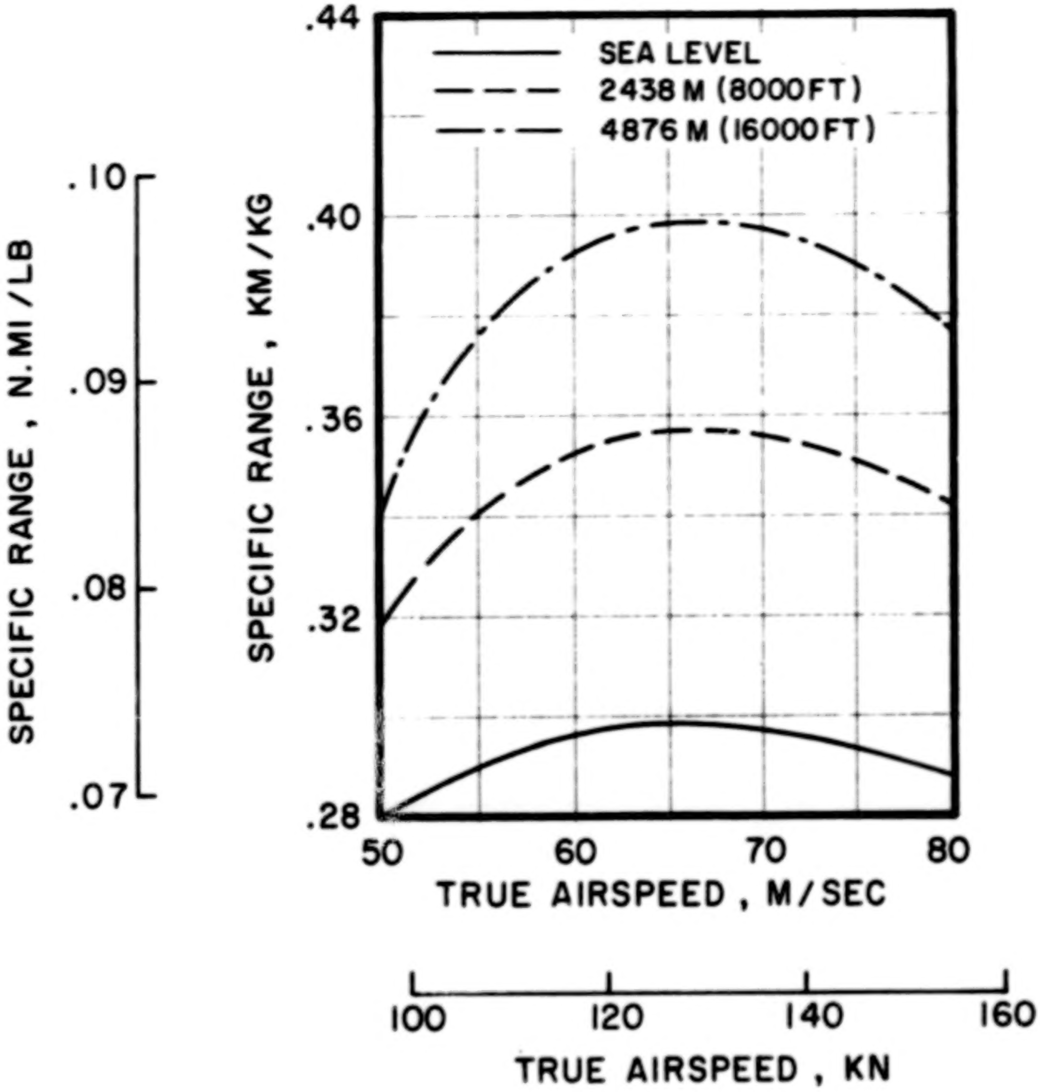
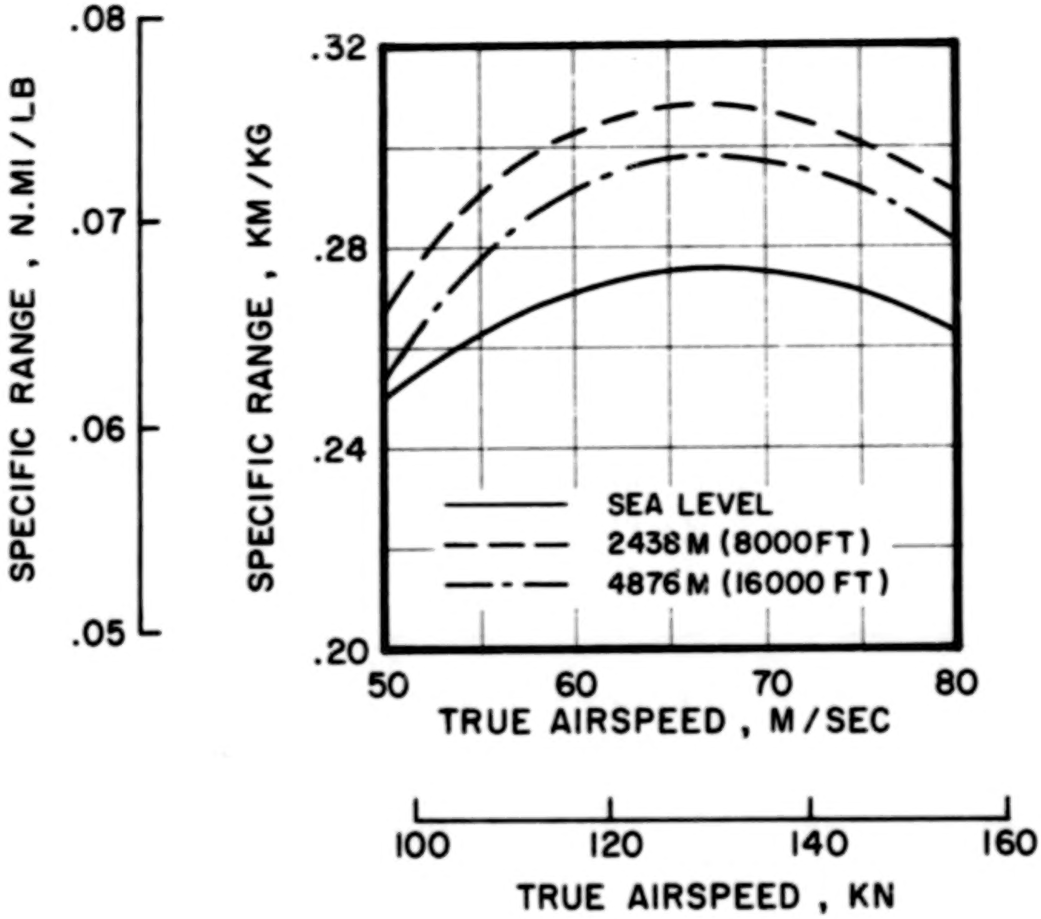


Figure 7. T64-GE-413 Engine Fuel Flow, ISA.



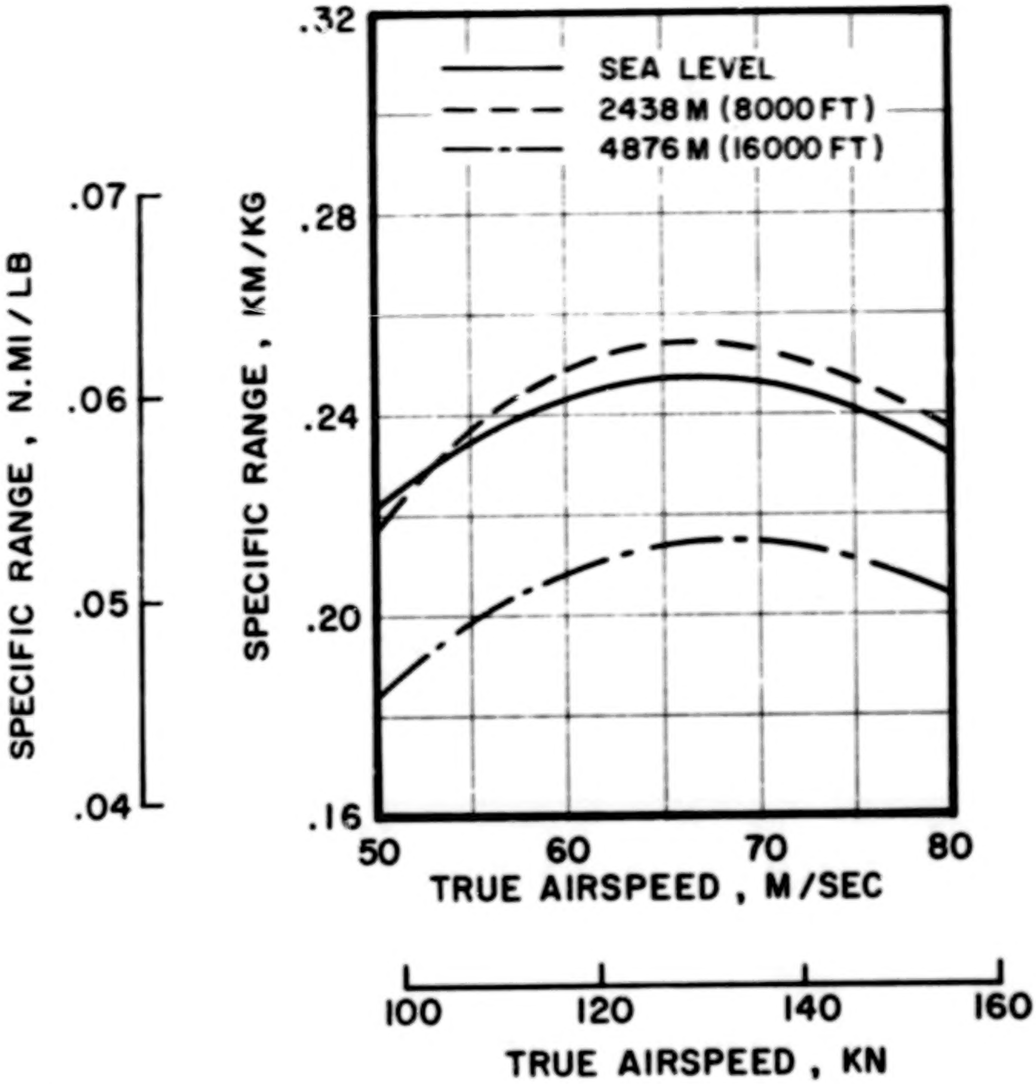
(a) GW = 11790 kg (26000 lb)

Figure 8. Specific Range Sensitivity to Airspeed (Best rpm, Zero Headwind, 15°C).



(b) GW = 15420 kg (34000 lb)

Figure 8. - Continued.



(c) GW = 19050 kg (42000 lb)

Figure 8. - Concluded.

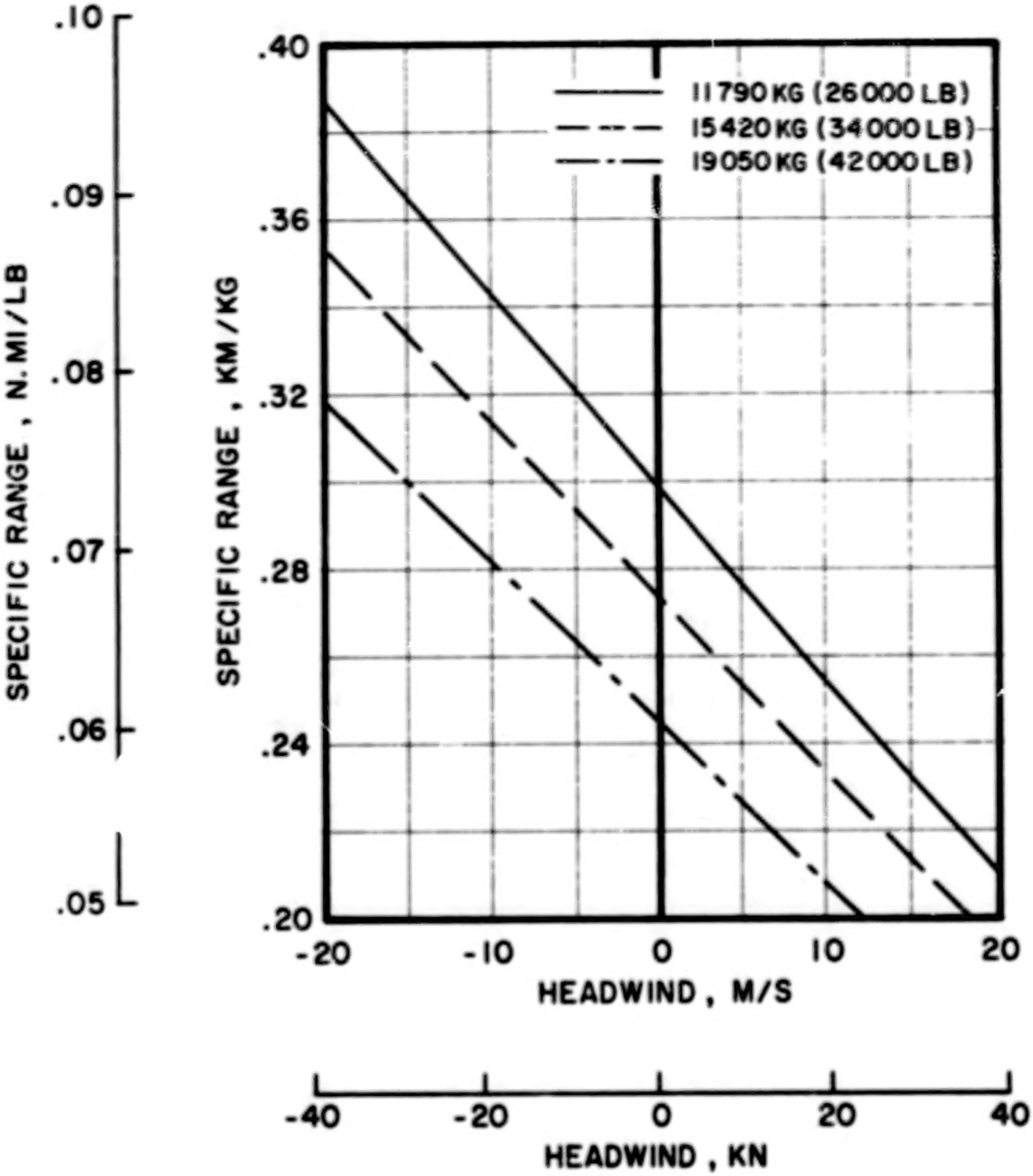
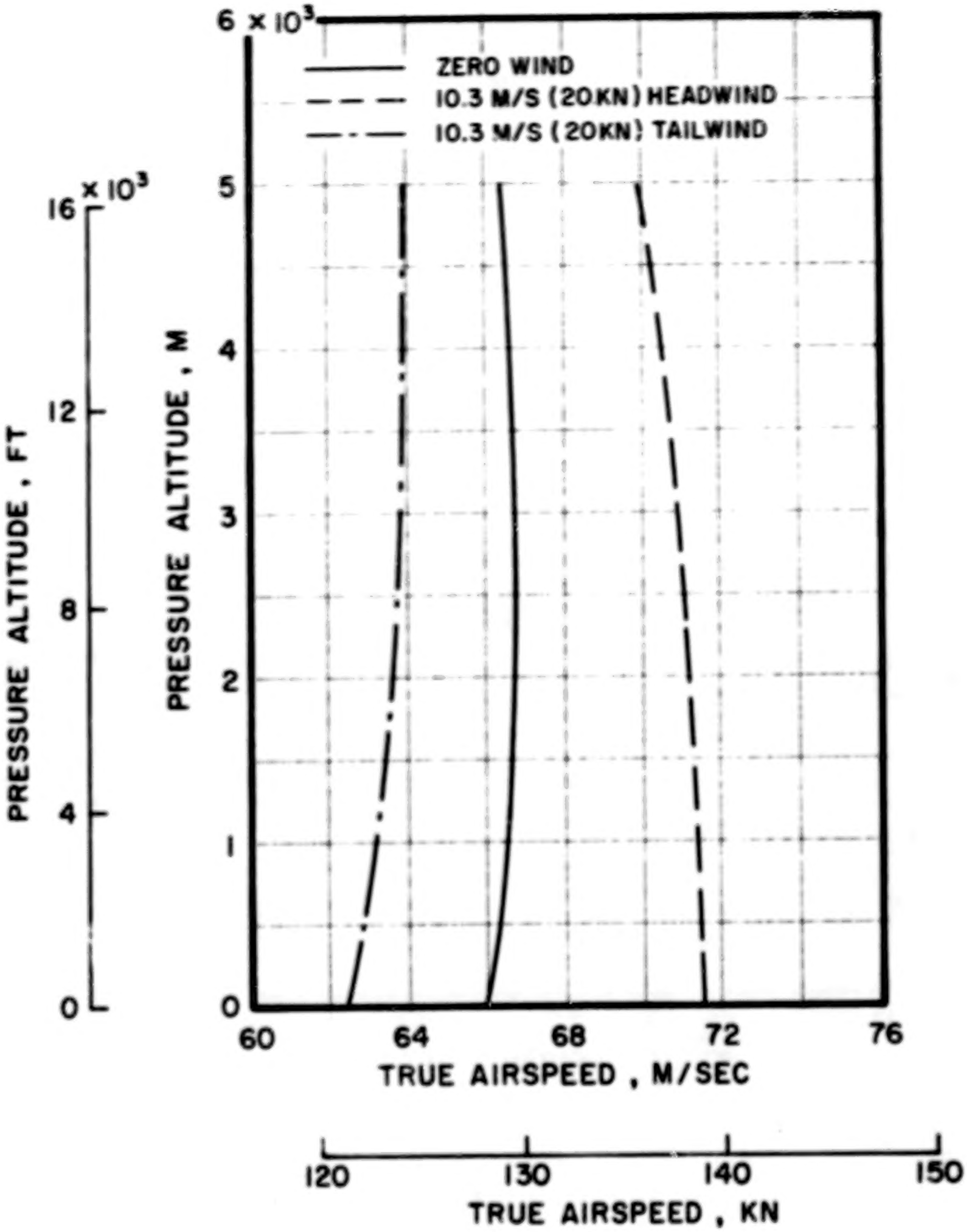
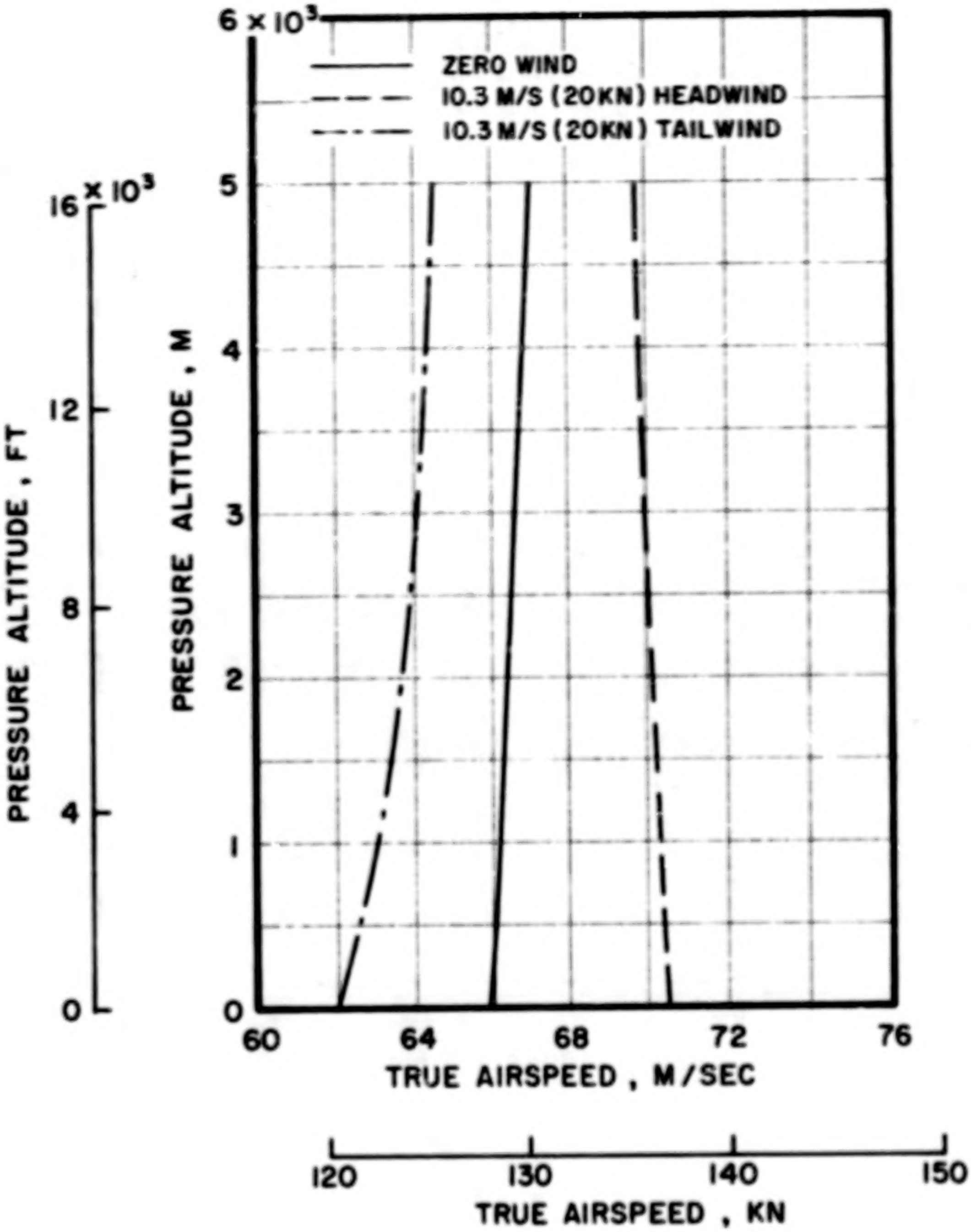


Figure 9. Specific Range Sensitivity to Headwind (Best Airspeed, Best rpm, Sea Level ISA).



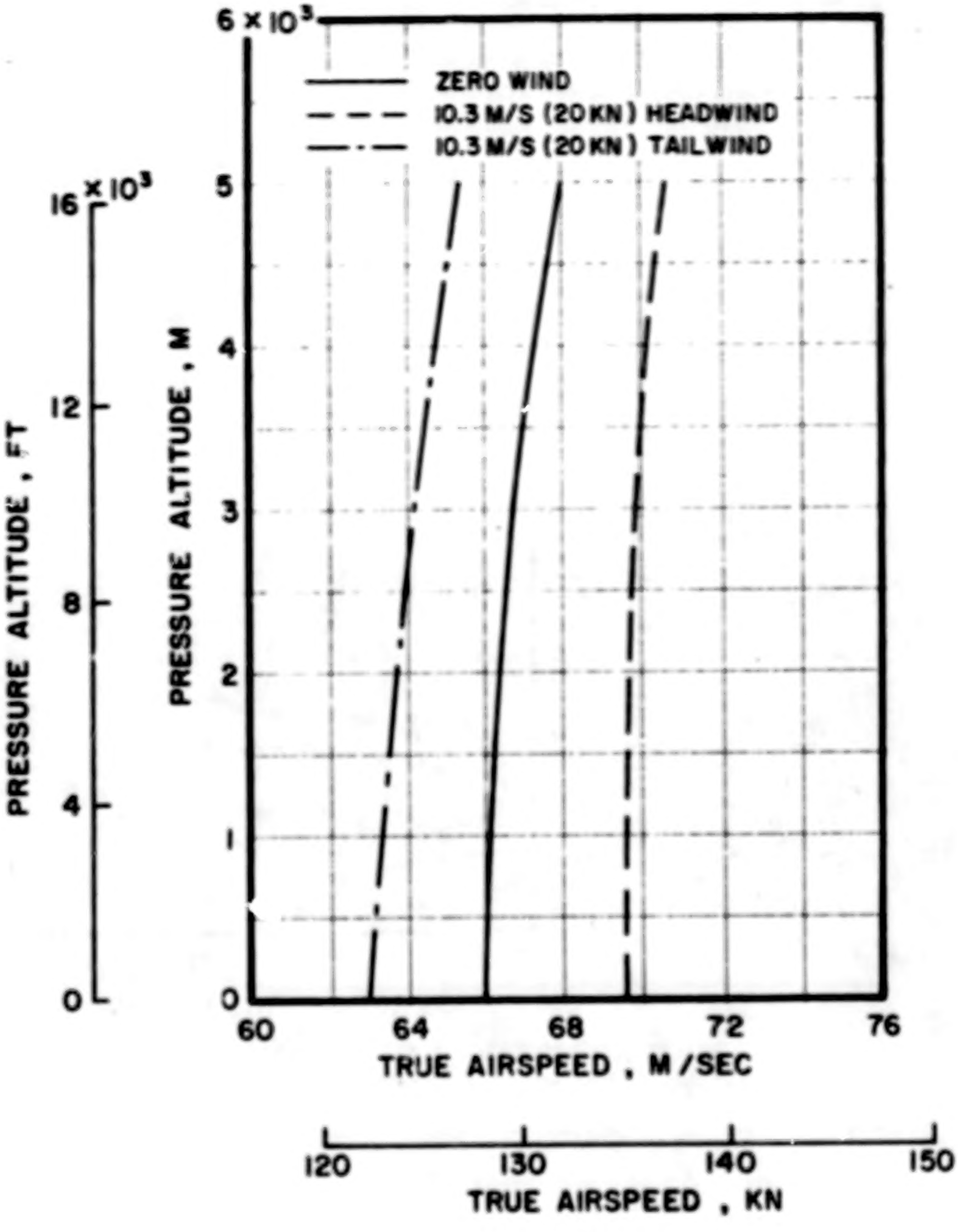
(a) GW = 11790 kg (26000 lb)

Figure 10. Best Range Airspeed (Best rpm, 15°C).



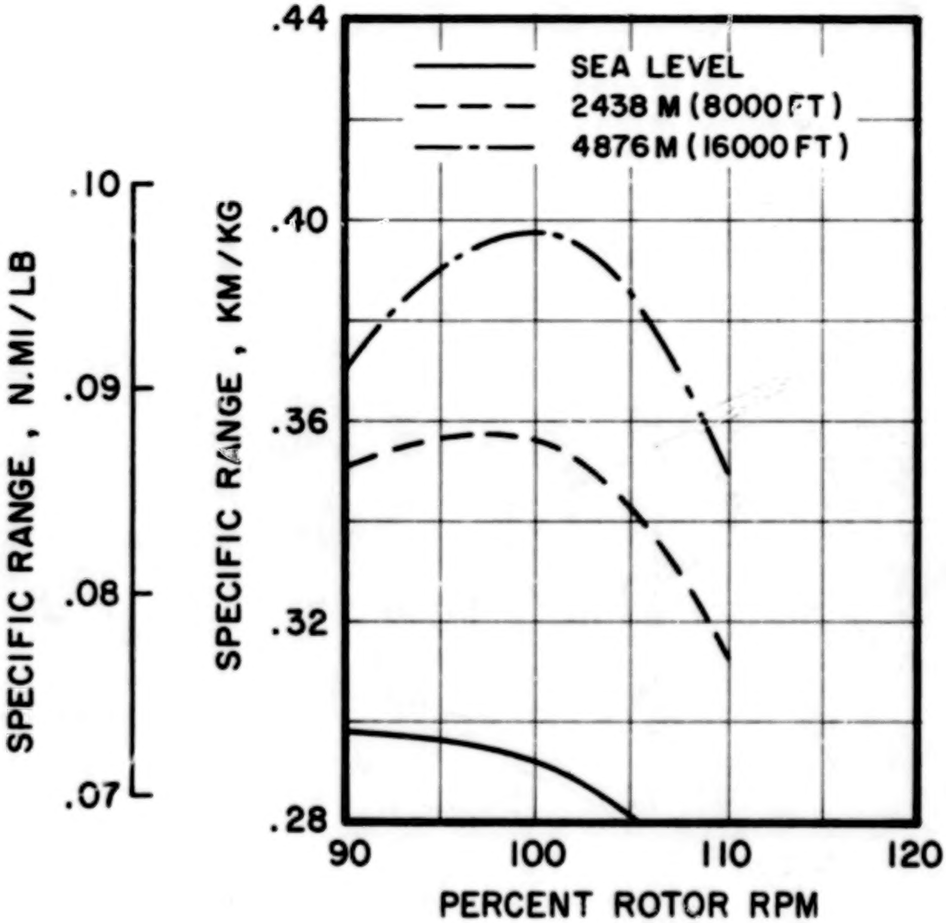
(b) GW = 15420 kg (34000 lb)

Figure 10. - Continued.



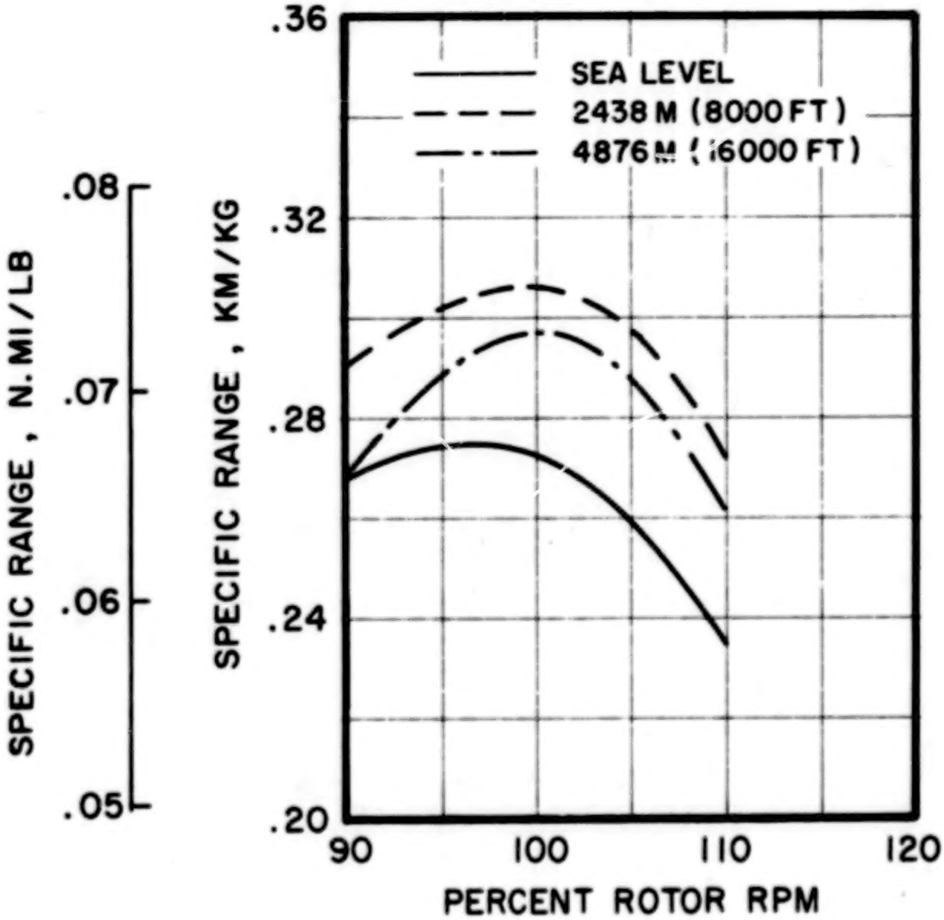
(c) GW = 19050 kg (42000 lb)

Figure 10. - Concluded.



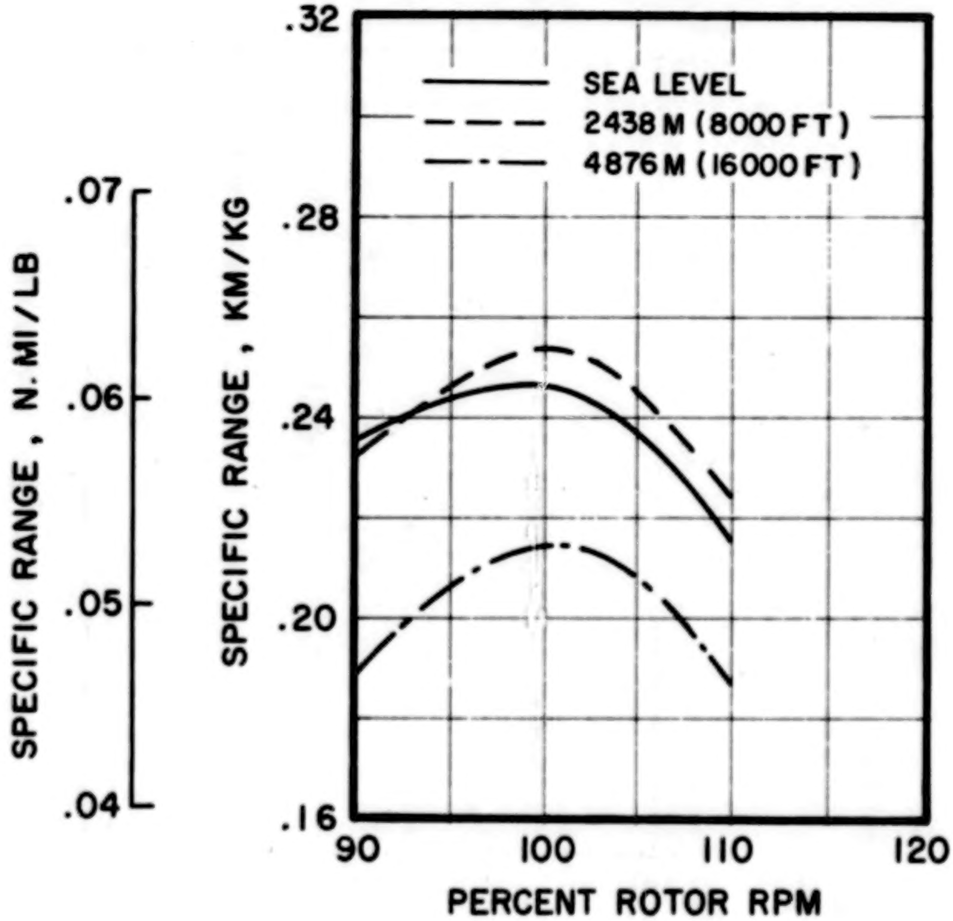
(a) GW = 11790 kg (26000 lb)

Figure 11. Specific Range Sensitivity to Rotor rpm (Best Airspeed, Zero Headwind, 15°C).



(b) GW = 15420 kg (34000 lb)

Figure 11. - Continued.



(c) GW = 19050 kg (42000 lb)

Figure 11. - Concluded.

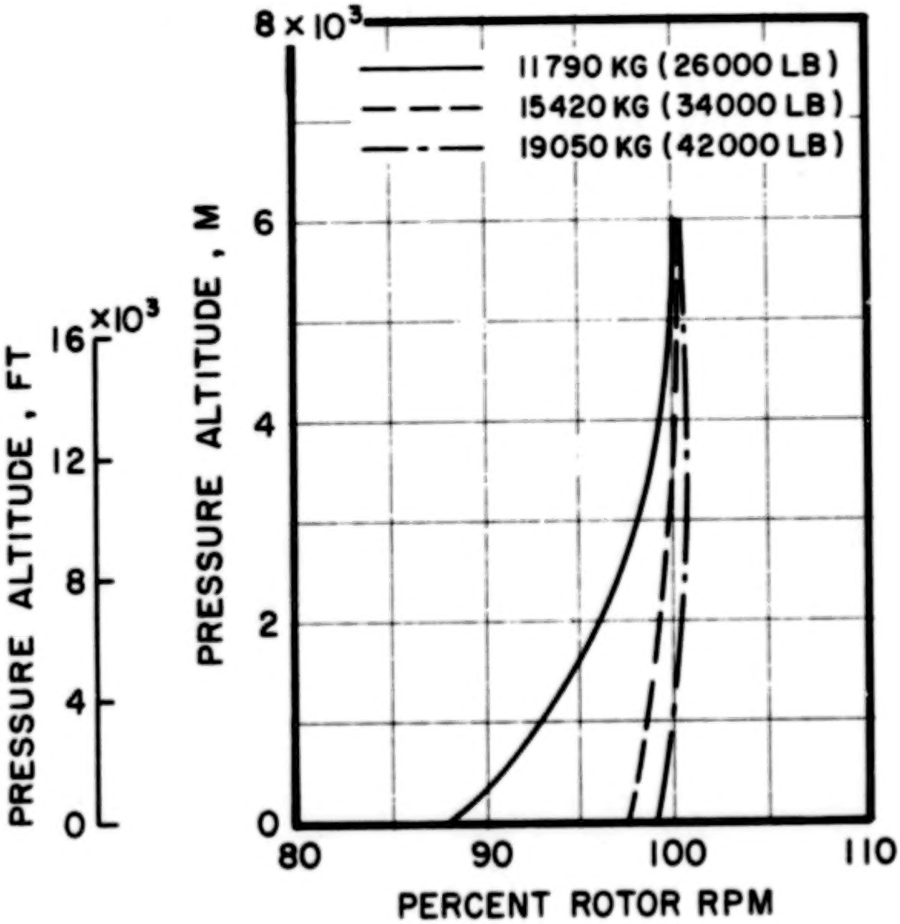


Figure 12. Best Range Rotor rpm (Best Airspeed, 15°C).

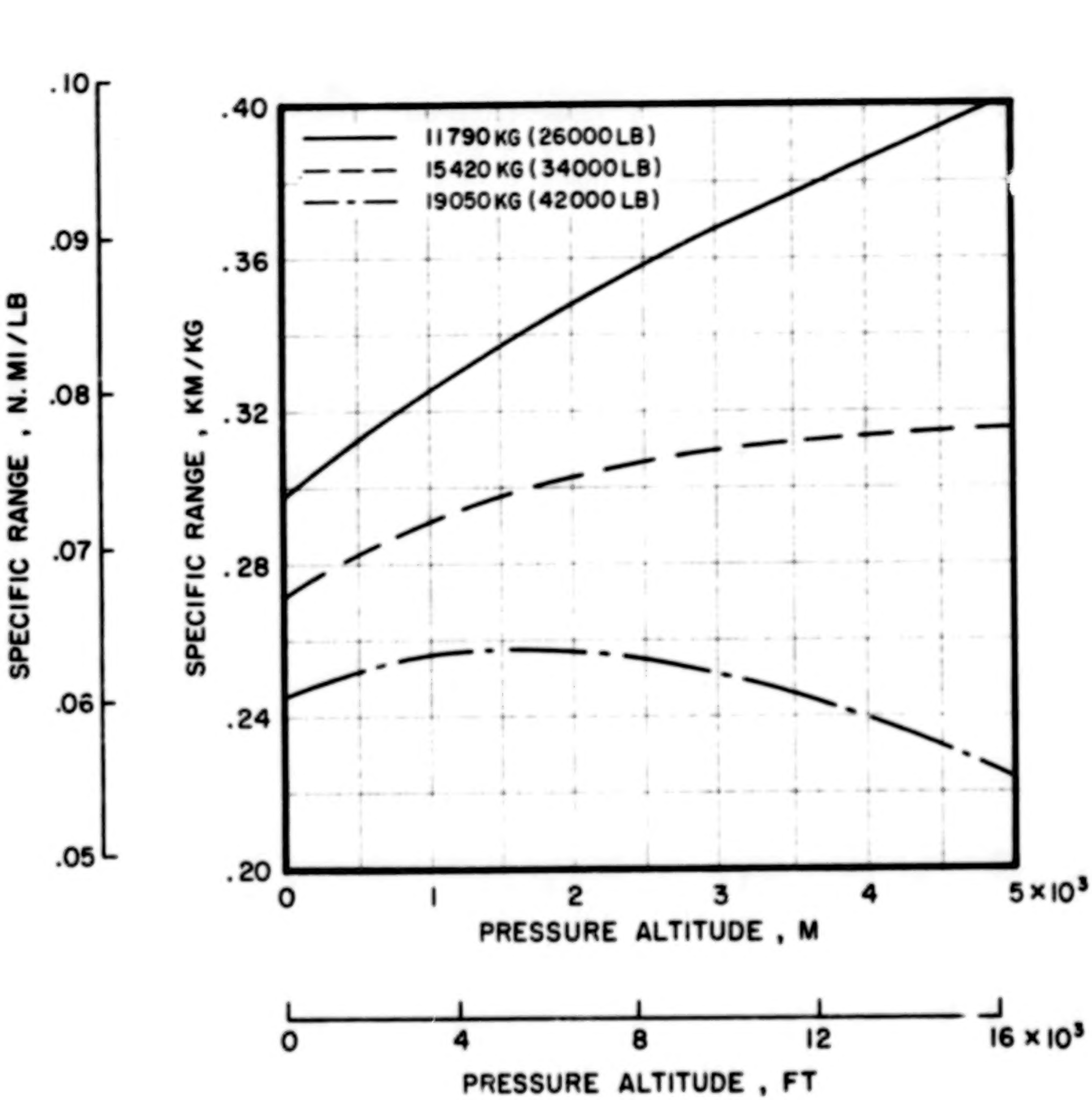


Figure 13. Best Specific Range for ISA and Zero Headwind.

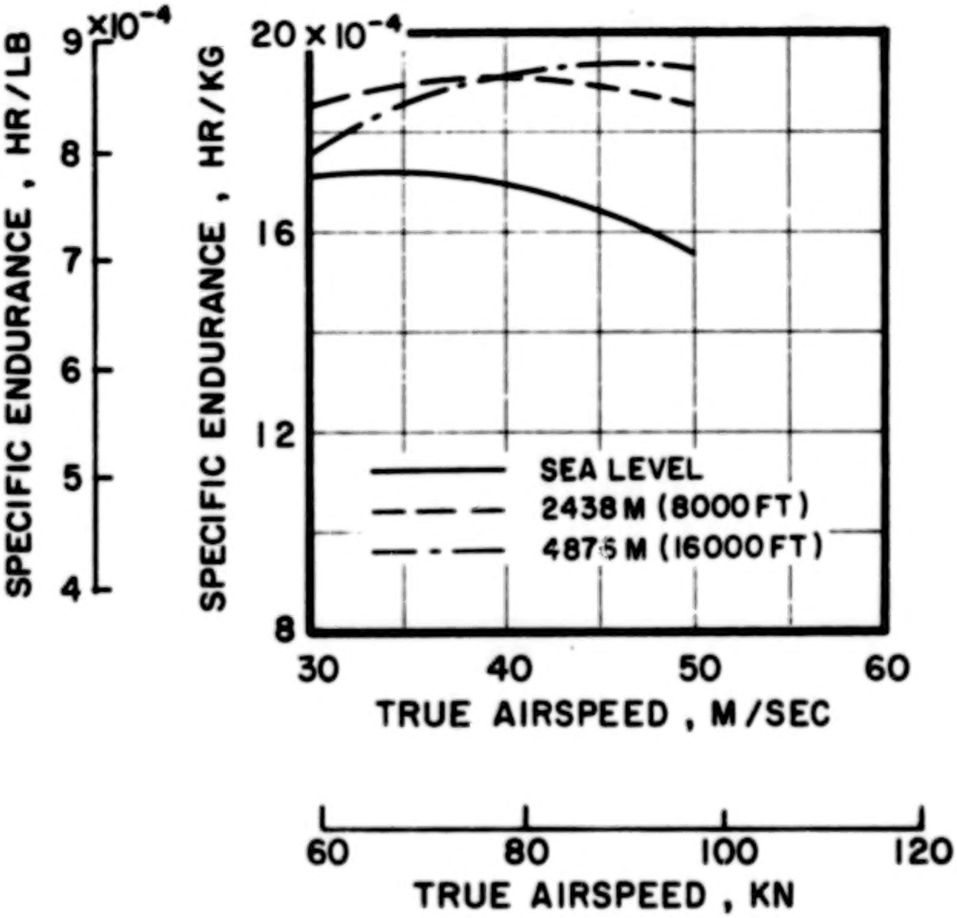
Minimum Fuel Consumption - Endurance

Flight conditions resulting in minimum fuel consumption for a given endurance were developed by combining the output of the power required analysis with the engine fuel flow performance illustrated in Figure 7. The trends and relationships thus developed were then programmed using curve-fit techniques.

Specific endurance was used as the measure of fuel efficiency for a given endurance. This parameter is equal to unit time per unit of fuel weight and is the reciprocal of total fuel flow. It is expressed as hours per kilogram or hours per pound.

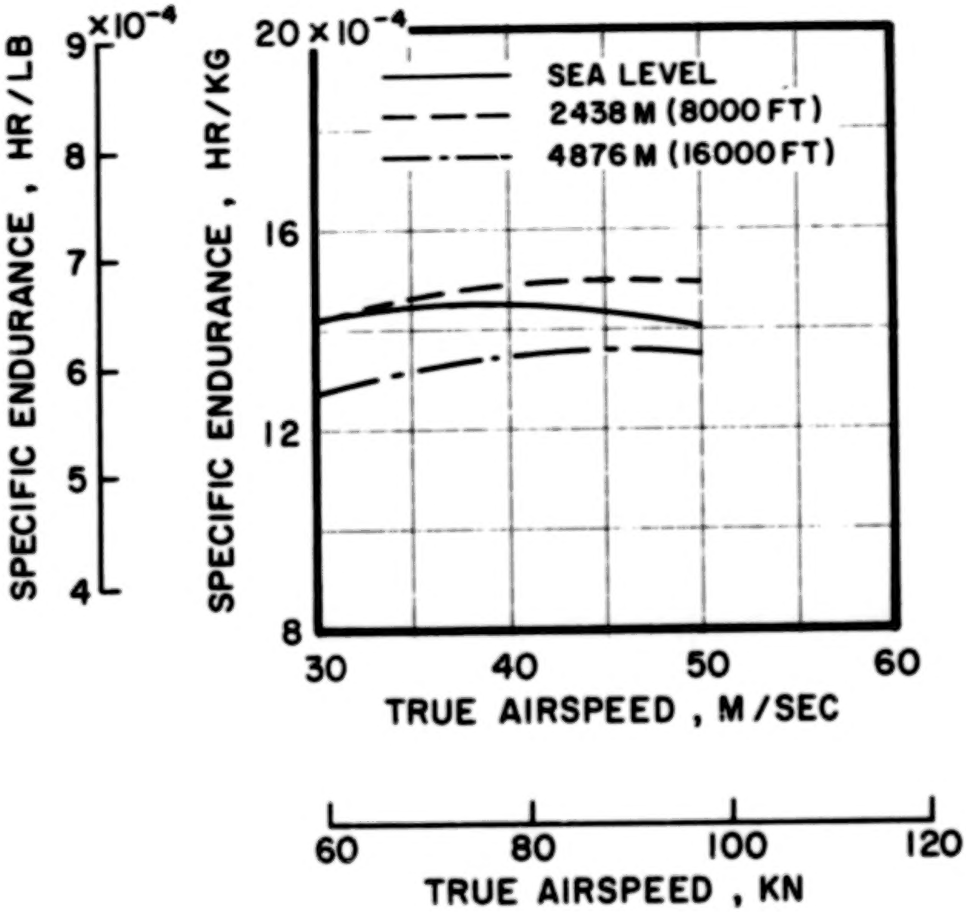
Specific endurance sensitivity to airspeed is illustrated in Figure 14 for a range of gross weights and altitudes. Optimum true airspeed (Figure 15) ranges from 34 to 48 m/sec (65 to 95 knots). Unlike for specific range, headwind does not influence best endurance conditions except that it changes the relationship between airspeed and ground speed. As shown in Figures 16 and 17, best endurance rotor rpm varies from less than 80 percent to over 100 percent depending on gross weight and altitude.

Figure 18 shows the best achievable specific endurance as a function of gross weight and altitude for ISA temperature.



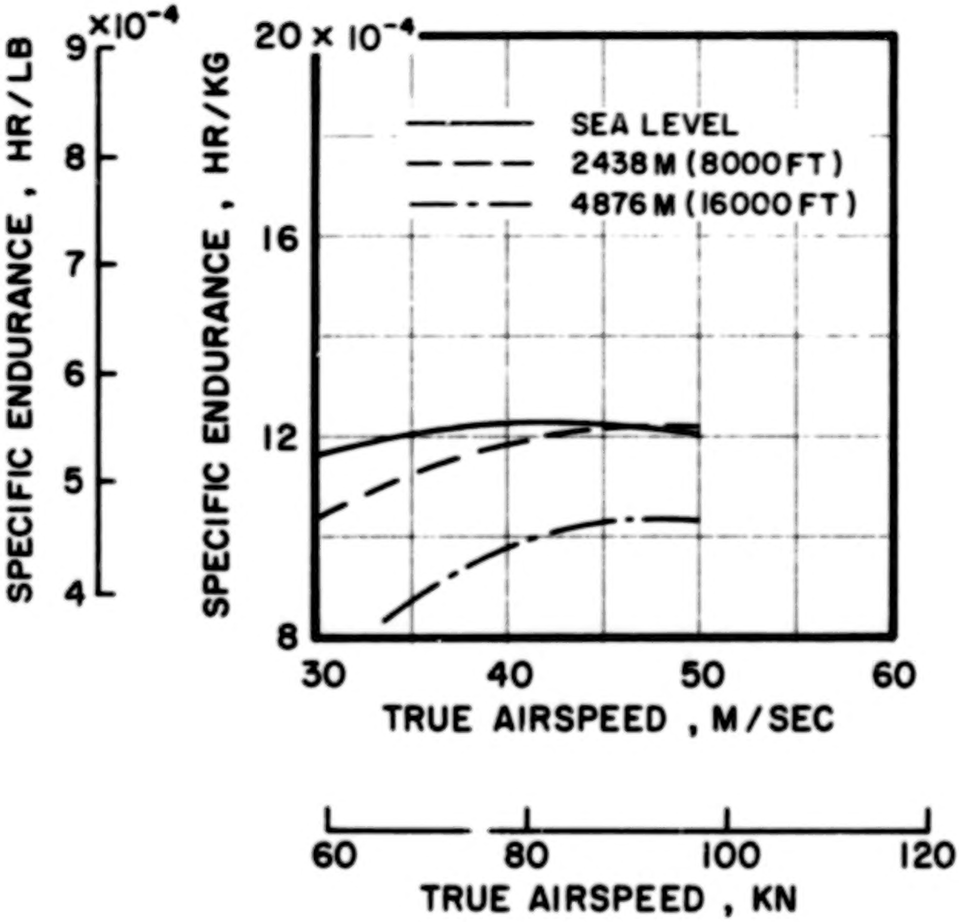
(a) GW = 11790 kg (26000 lb)

Figure 14. Specific Endurance Sensitivity to Airspeed (Best rpm, 15°C).



(b) GW = 15420 kg (34000 lb)

Figure 14. - Continued.



(c) GW = 19050 kg (42000 lb)

Figure 14. - Concluded.

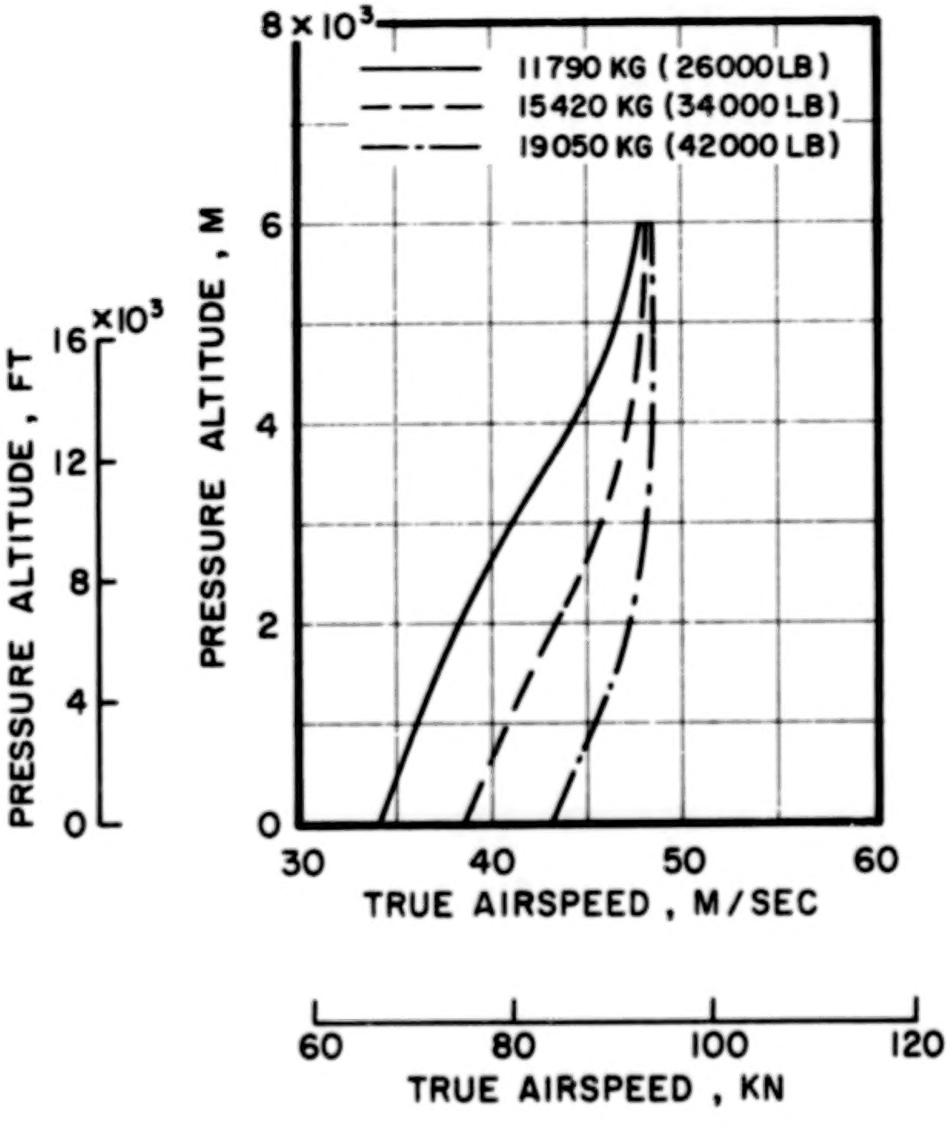
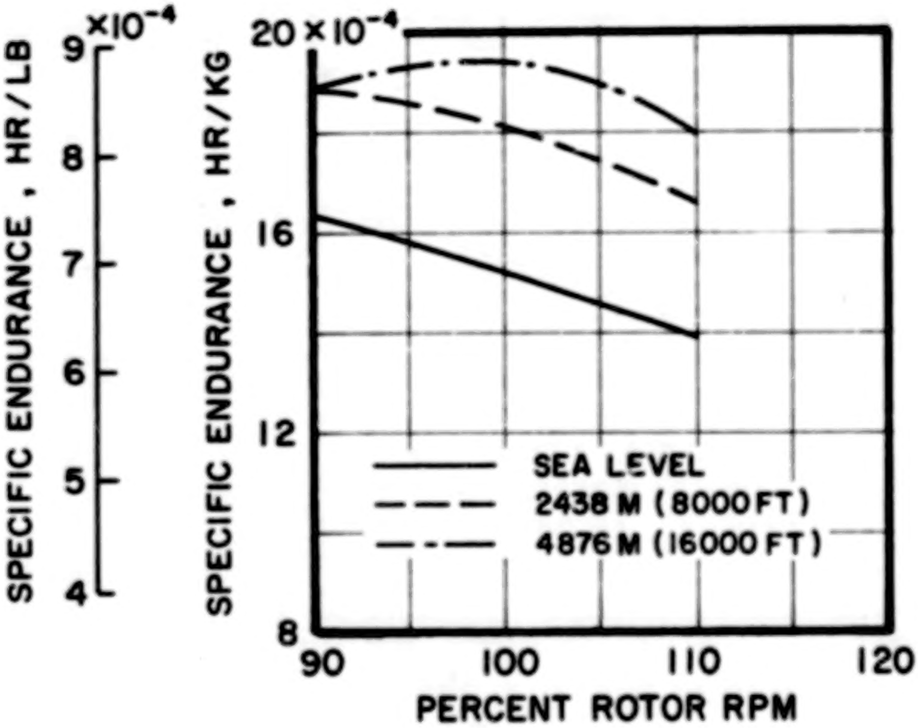
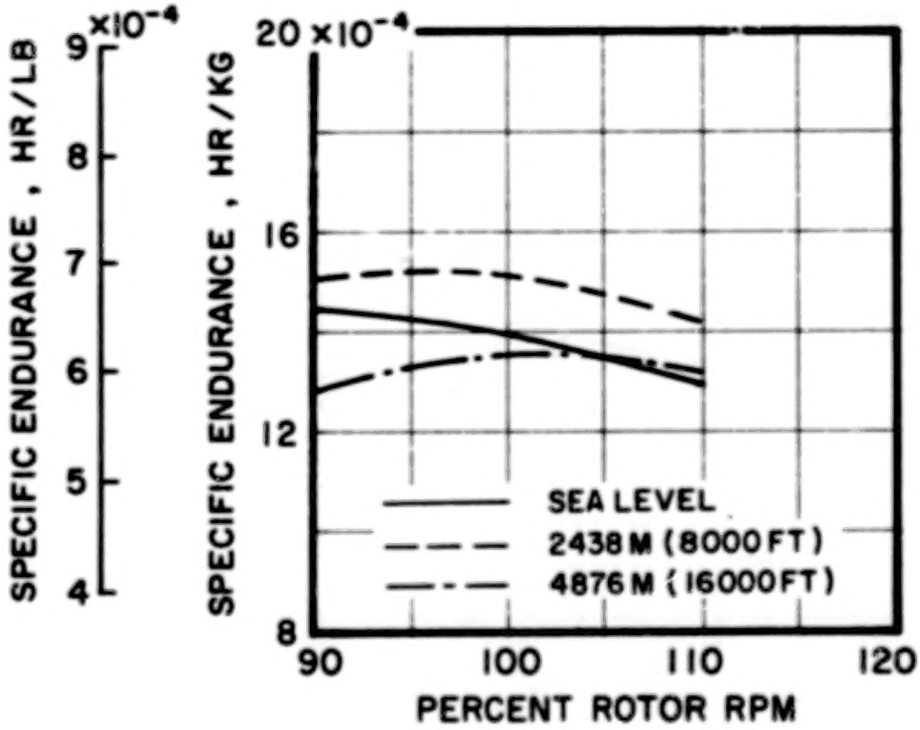


Figure 15. Best Endurance Airspeed (Best rpm, 15°C).



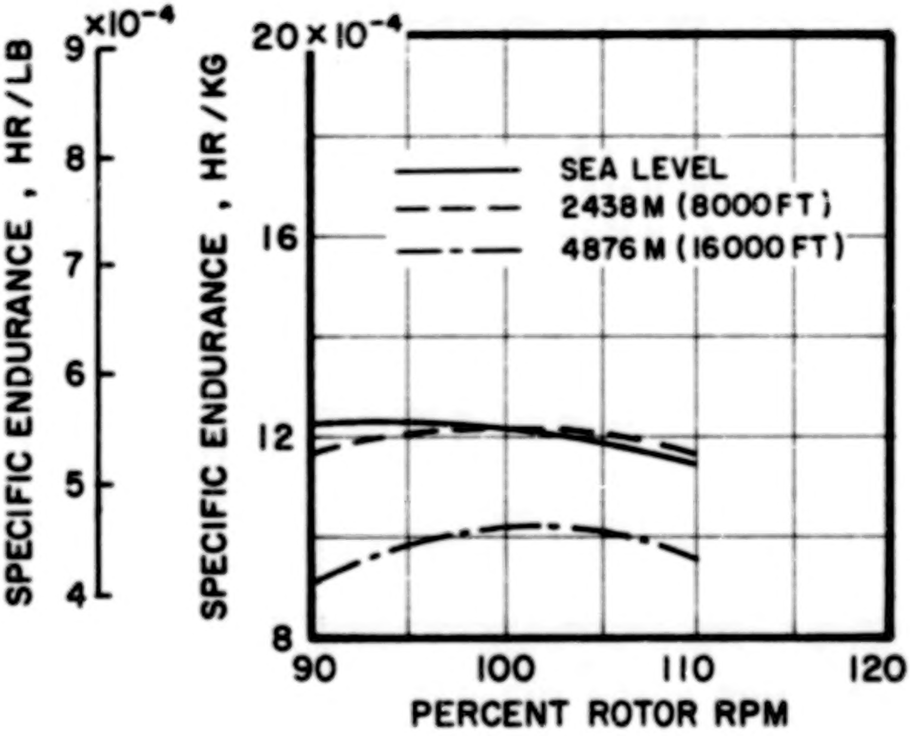
(a) GW = 11790 kg (26000 lb)

Figure 16. Specific Endurance Sensitivity to Rotor rpm (Best Airspeed, 15°C).



(b) GW = 15420 kg (34000 lb)

Figure 16. - Continued.



(c) GW = 19050 kg (42000 lb)

Figure 16. - Concluded.

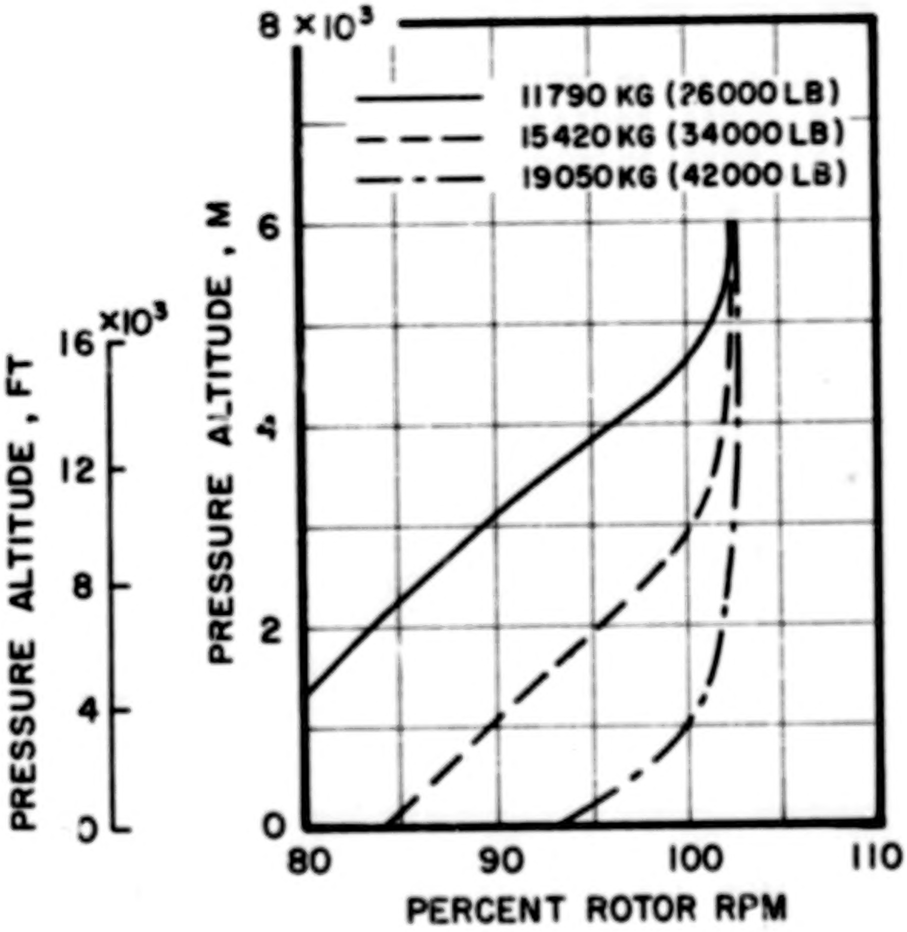


Figure 17. Best Endurance Rotor rpm (Best Airspeed, 15°C).

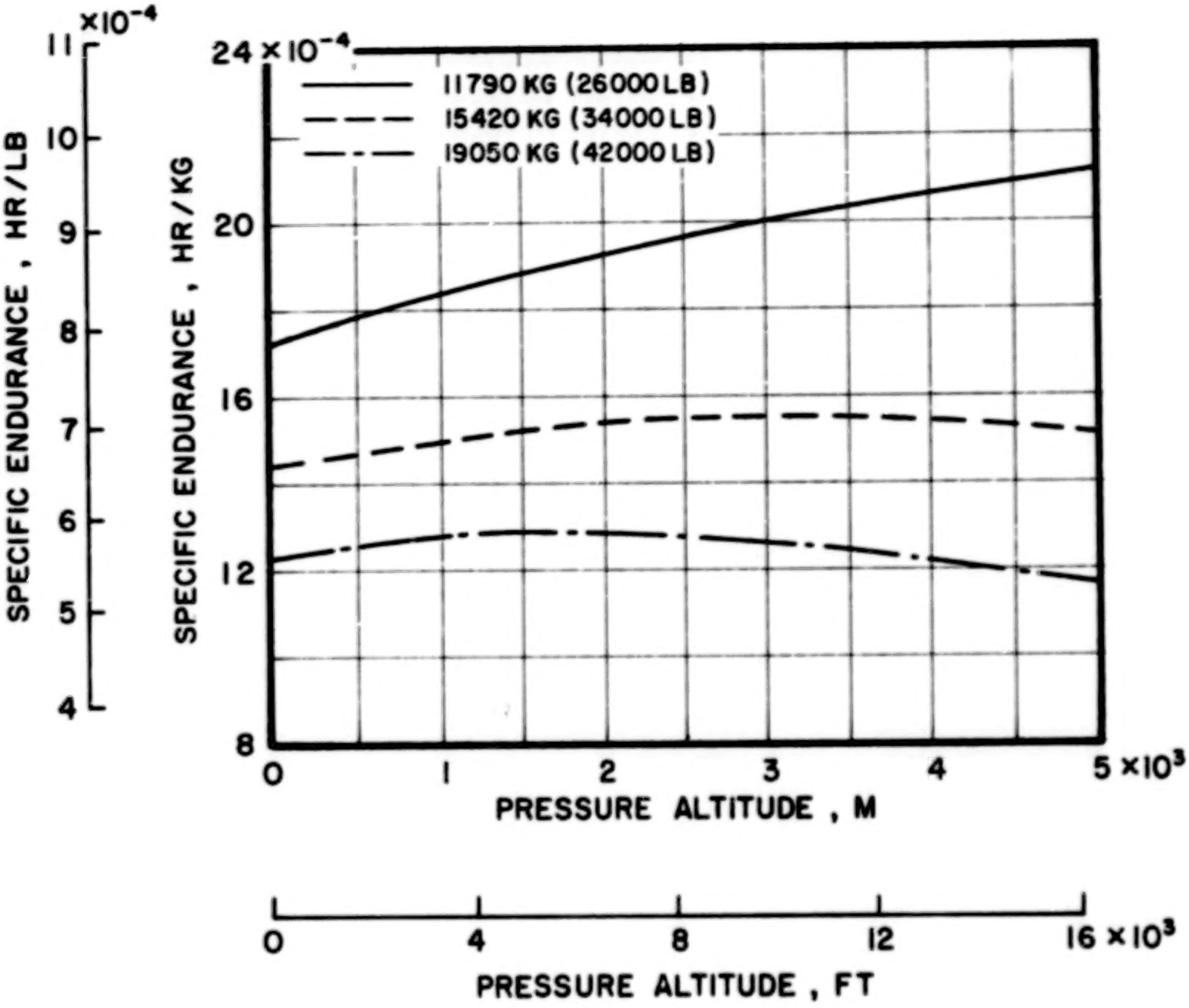


Figure 18. Best Specific Endurance for ISA.

Maximum Speed

Maximum sustained airspeed is limited by one of three independent criteria: power available, blade stall, or structural design.

Power limited speed occurs at the match of power required and available normal rated power. It was defined by calculating power required versus airspeed as a function of gross weight, altitude, and temperature, and superimposing the T64-413 power available defined in Figure 19. Two-engine operation is assumed. The CH-53D transmission limits per-engine continuous power to 3244 metric hp (3200 hp).

Blade stall manifests itself as increasing control system loads which are registered on the cockpit cruise guide indicator. The onset of stall is a function of the retreating blade angle of attack, which in turn depends on the blade lift requirement (gross weight), retreating blade speed (airspeed and rotor rpm) and air density (altitude and temperature). The relationship between these parameters can be approximated as:

$$\text{Retreating blade angle} \approx \frac{k \times GW}{\text{air density} \times (\text{tip speed} - \text{airspeed})^2}$$

where k is a constant for a given helicopter.

Solving for airspeed and defining a new constant, k_{st}, representing the onset of stall, results in:

$$V_{st} = \text{tip speed} - k_{st} \left(\frac{GW}{\text{density ratio}} \right)^{1/2}$$

The constant, k_{st}, is derived empirically from measured control system load characteristics. For the CH-53, $k_{st} = 0.8978$ for speed units of meters/second and weight units of kilograms. ($k_{st} = 1.1745$ for speed units of knots and weight units of pounds).

Structurally limited speed, or red-line speed, is that corresponding to the dynamic pressure for which the aircraft structure is designed and substantiated. Since it represents a constant dynamic pressure, red-line speed is a constant indicated (calibrated) airspeed, which means that the corresponding true airspeed varies as the inverse root square of the density ratio.

Power limited speed was defined as a function of gross weight, altitude, temperature, and rotor rpm and the resulting trends were programmed using curve-fit techniques. Stall and structural speed limits were programmed analytically using the above described relationships. The maximum speed program outputs the lowest of the three speeds for the flight condition specified.

Typical maximum sustained speed capability is depicted in Figure 20 for ISA conditions and 100 percent rotor rpm.

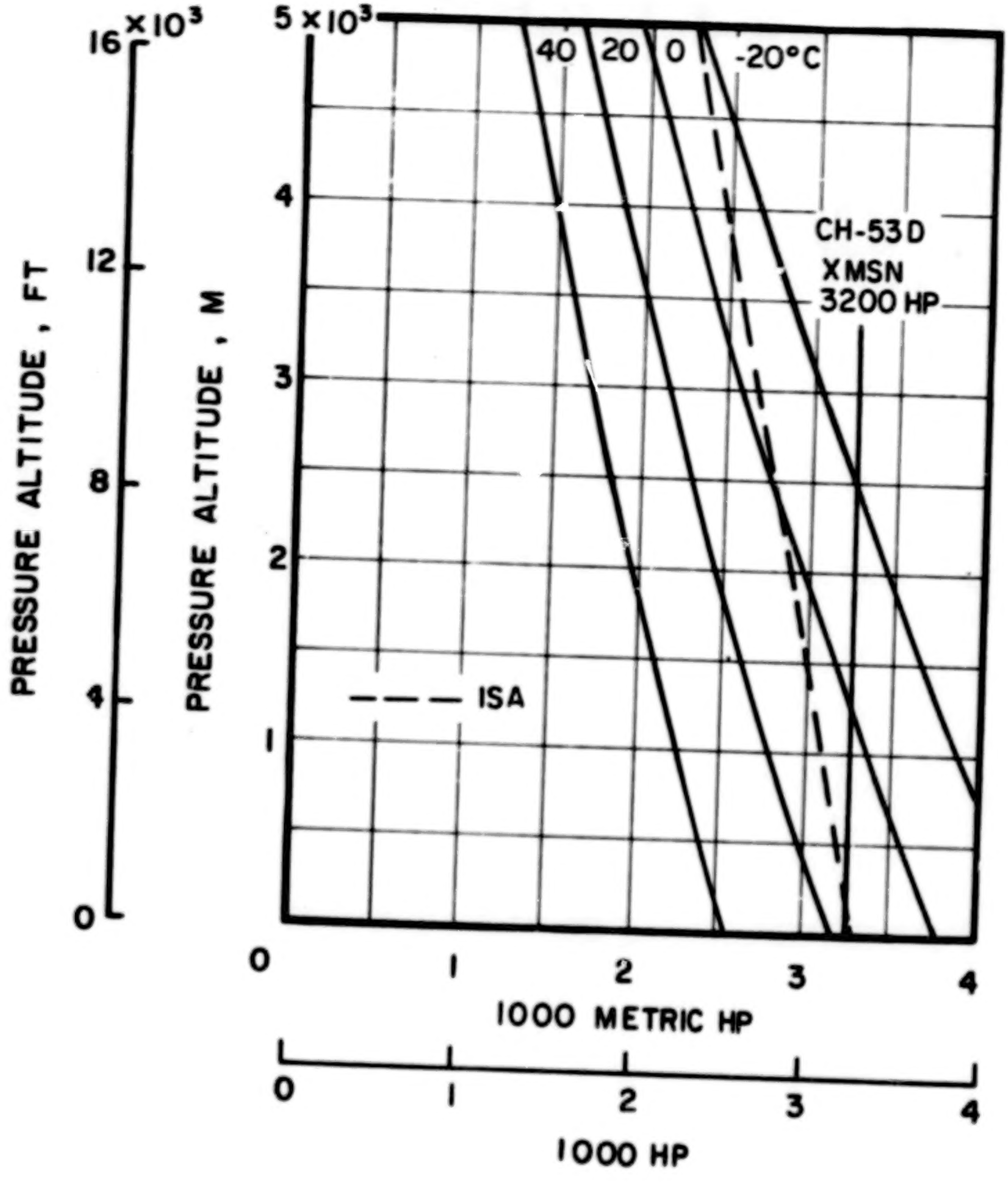


Figure 19. T64-GE-413 Maximum Continuous Power.

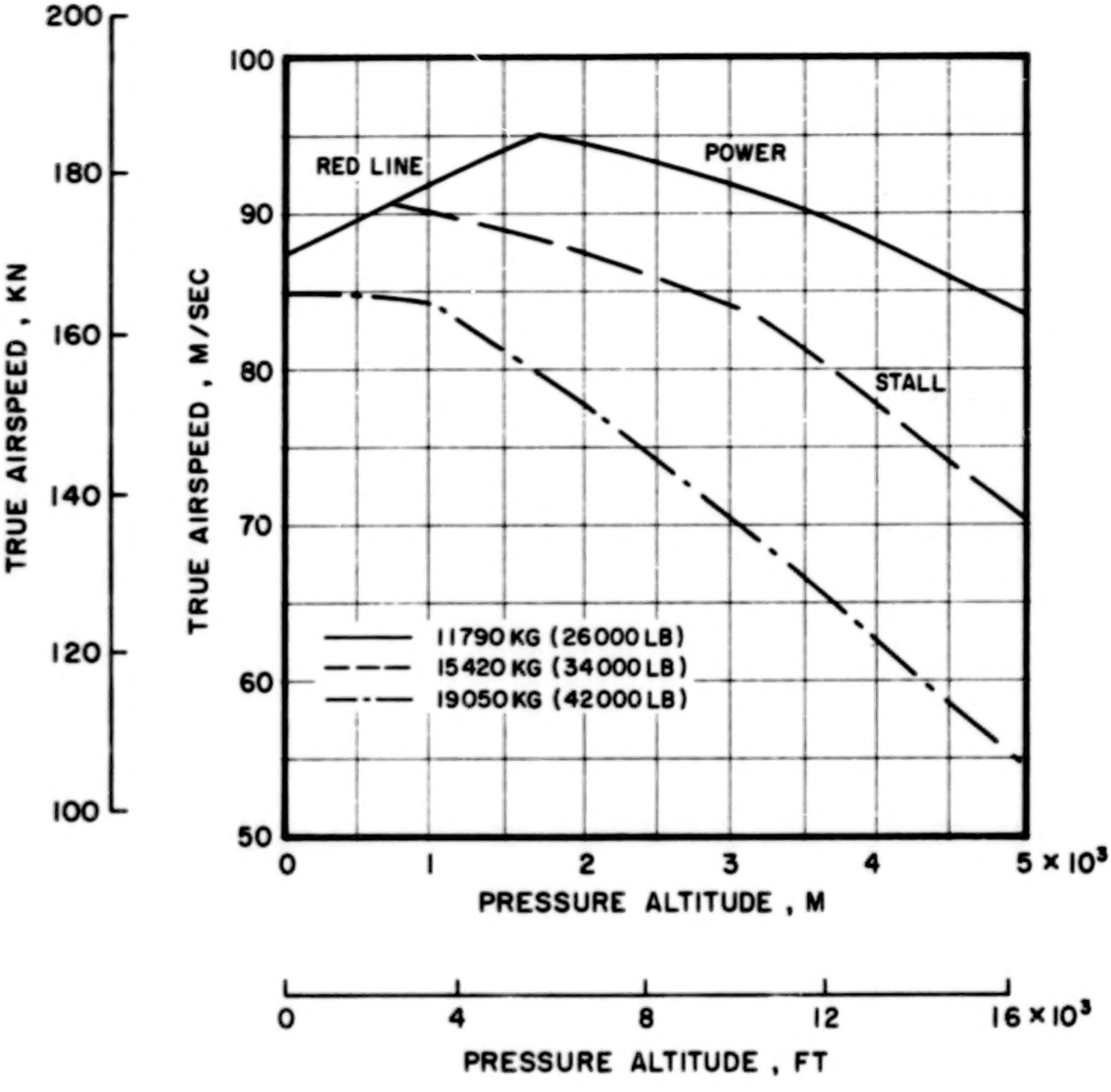


Figure 20. Maximum Sustained Airspeed (100% rpm, ISA).

Noise Methodology

Helicopter external noise arises from three basic sources: the main rotor, the tail rotor, and the engines. The relative dominance of a particular source depends on the helicopter configuration, the flight regime, and the observer position.

Main rotor noise consists of rotational harmonics starting at the fundamental blade passage frequency (18.5 Hz for the CH-53) plus a broadband distribution at higher frequencies. Tail rotor noise has a similar signature except that it is shifted up in frequency due to the higher rpm.

Engine noise is basically broadband in character, with levels peaking between 200 and 500 Hz. For the CH-53 there is also a narrow angle forward of the engine inlet where compressor tones can be heard at 8000 Hz.

Human hearing is most acute in the frequency range from 500 to 4000 Hz. For the same pressure level, higher frequency noise is generally more annoying. To measure annoyance, the observed noise pressure frequency spectrum is weighted according to the sensitivity of the human ear. This results in units of Percieved Noise Level, PNL. Annoyance is also a function of exposure time. The time factor is accounted for by the Effective Perceived Noise Level, EPNL, which is the PNL integral over the exposure period in 1/2-second intervals. EPNL is the unit of noise measurement accepted by the FAA for aircraft certification. A complete discussion of EPNL and its method of calculation is presented in Reference 1.

The maximum noise produced by an overflying helicopter is observed directly under the flight path (ignoring wind effects). Although overall community noise impact depends on the total noise footprint, it is sufficient for the purpose of establishing minimum noise procedures to trend noise along the flight path centerline.

A point on the ground 1158 meters (3800 feet) along the flight path centerline from the takeoff (or touchdown) threshhold was selected as the noise measurement point. This point corresponds to the observer position when the helicopter is 122 meters (400 feet) overhead during a six degree climb or descent angle, which is the current FAA criterion.

CH-53 flyover noise was predicted by the Sikorsky Generalized Helicopter Noise Model described in Reference 2. This model calculates the PNL time history and resulting EPNL generated by the combination of main rotor, tail rotor, and engines.

Level flight and climb noise prediction is relatively straightforward. Descent noise prediction is a greater challenge because of interaction between the rotor and its own wake.

During some descent conditions, the main rotor flies into its own wake. The strong circulations present in the wake, particularly in the wound-up tip vortices, induce high local blade angles of attack in portions of the rotor disc. This in turn induces sharp fluctuations in blade section profile drag which are observed in the far field as impulsive noise. To treat this phenomenon, a rotor performance program was run with a variable inflow wake representation, and the resulting profile drag force distribution was input to the rotor noise model. Figure 21 illustrates the typical distribution of local blade drag loading for descent angles of three, six, and nine degrees. It is apparent that the six degree descent produces the greatest drag perturbations.

Figure 22 shows typical correlation of predicted level flight flyover PNL with that measured during CH-53 flight tests at Wallops Island Flight Center in August of 1977. Predicted noise is slightly higher, resulting in an EPNL of 100 dB compared to the observed level of 98.5 dB. Climb and descent measurements exhibited run-to-run variation due to difficulty in controlling flight path (radar track data were not available for correction purposes). However, the average measured six-degree descent EPNL was within one dB of the predicted value.

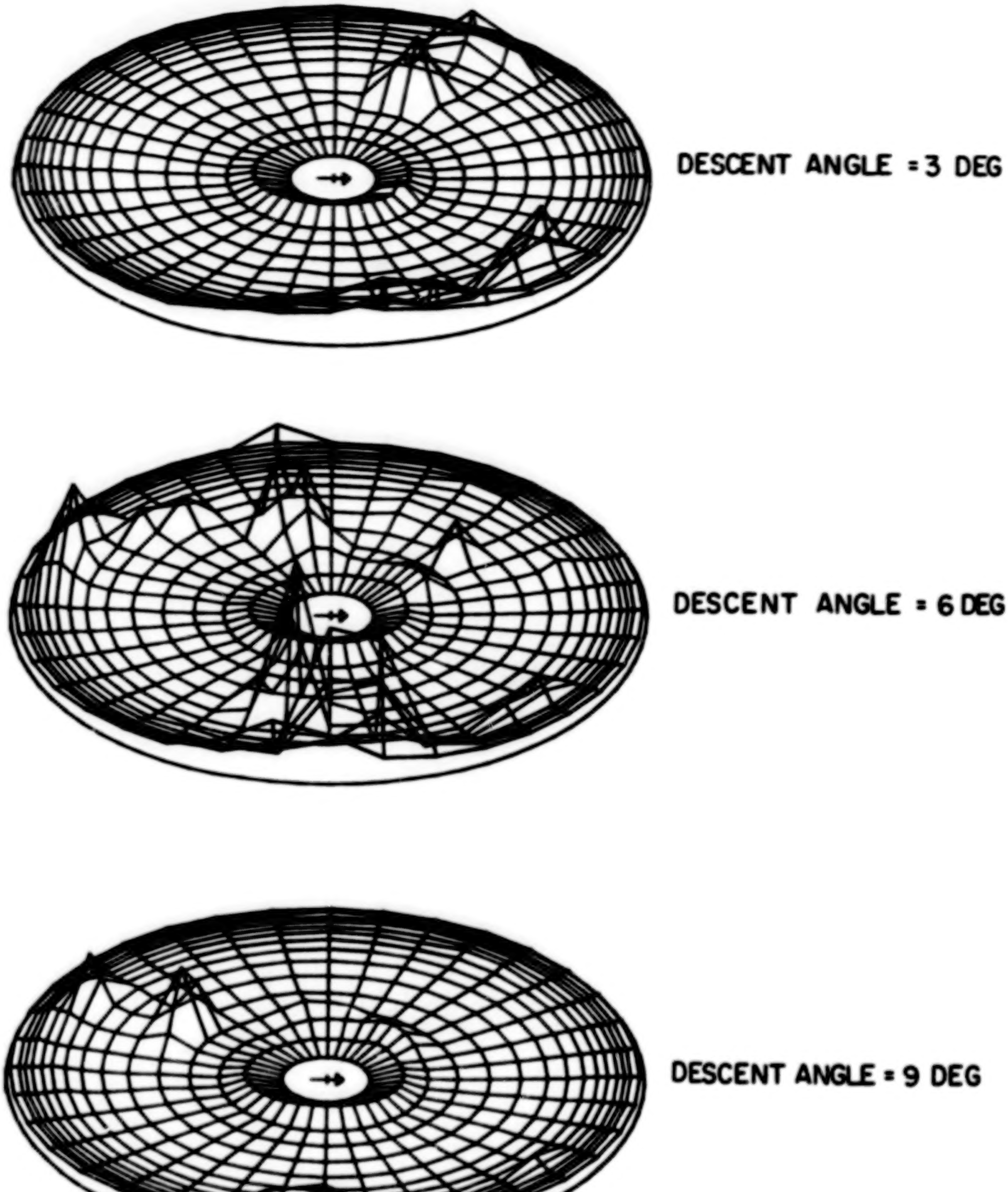


Figure 21. Blade Profile Drag Distribution at Various Descent Angles for GW = 19050 kg (42000 lb), Airspeed = 49 m/s (95 kt).

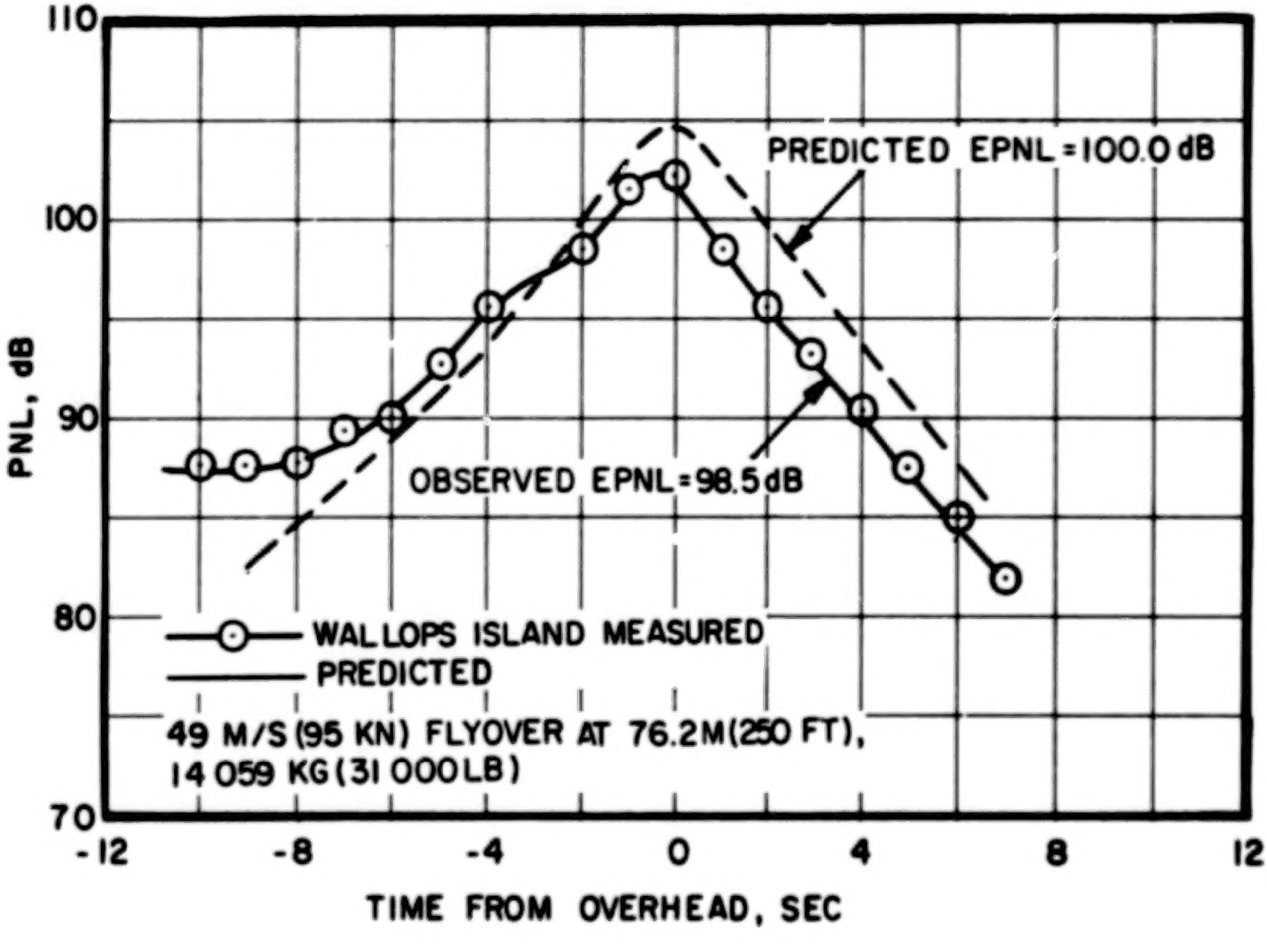


Figure 22. Correlation of Predicted and Observed Noise.

Takeoff Noise

The noise produced by the CH-53 during takeoff climbout increases with power level and decreases with distance to the observer. Steep climb angles require high power but increase the observer flyover altitude. The distance attenuation is more significant than the higher power, resulting in minimum observed noise at maximum achievable climb angle (see Figure 23).

Minimum noise is also achieved with low rotor rpm. This sensitivity is shown in Figure 24 in terms of advancing tip Mach number, which includes the effect of temperature. The normal rpm range of 95 to 105 percent represents an EPNL variation of about one dB.

Achievable CH-53 climb angle with 30-minute power is shown in Figure 25 as a function of gross weight and altitude. It ranges from about 8 degrees at maximum gross weight and high altitude to about 18 degrees at low gross weight and altitude. Because acceptable climb angle may be constrained to less than the power-limited capability by passenger comfort criteria or air traffic control considerations, the takeoff noise optimization program provides for optional input of a specified climb rate. Optimum rotor rpm is pre-loaded as a minimum of 100 percent; other values can be optionally input.

Climb angle is redefined in terms of the more readily controlled airspeed and climb rate parameters for output to the pilot.

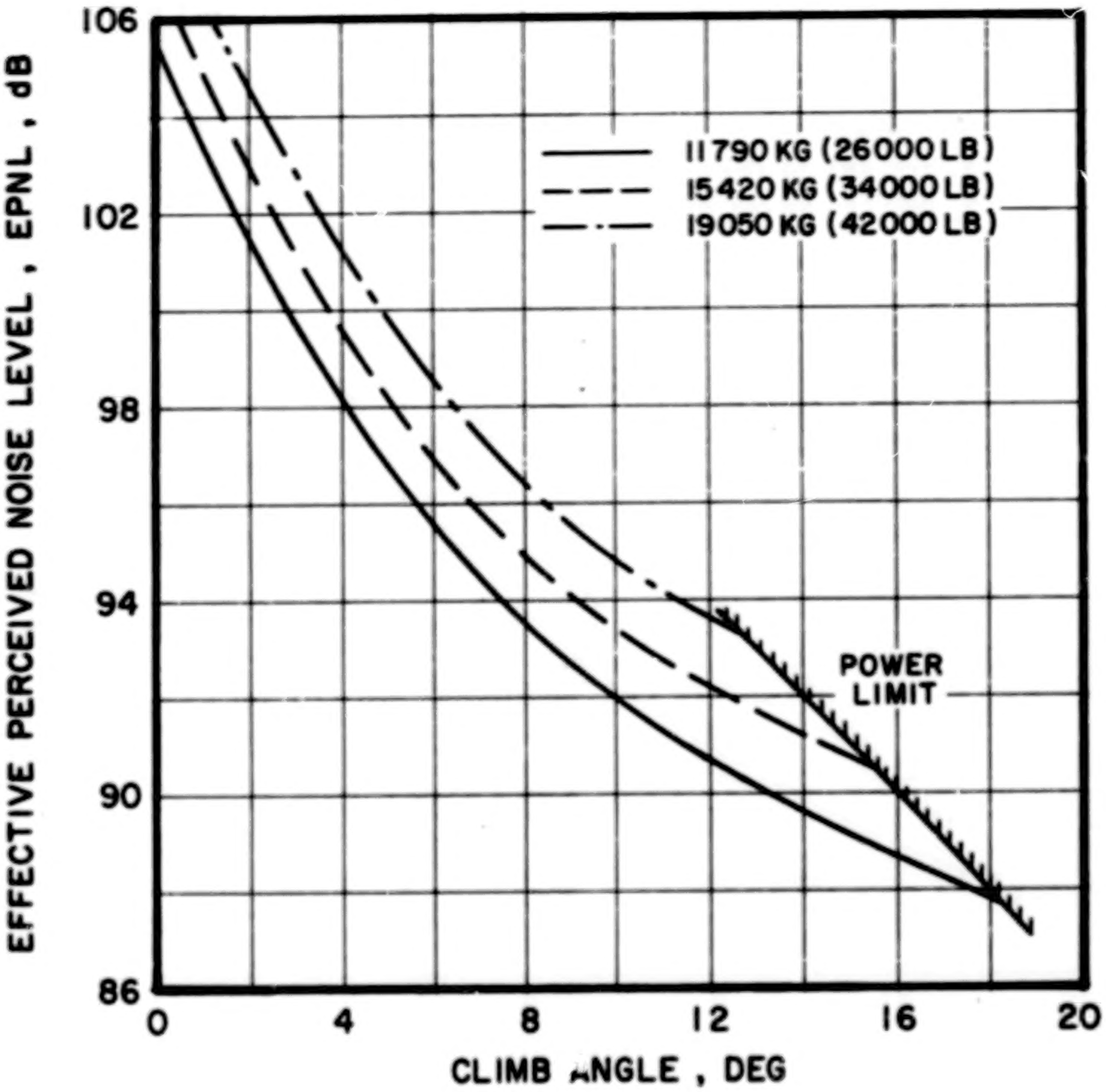


Figure 23. Noise Sensitivity to Climb Angle for Sea Level ISA, Airspeed = 49 m/s (95 kt), 95% rpm, 15°C.

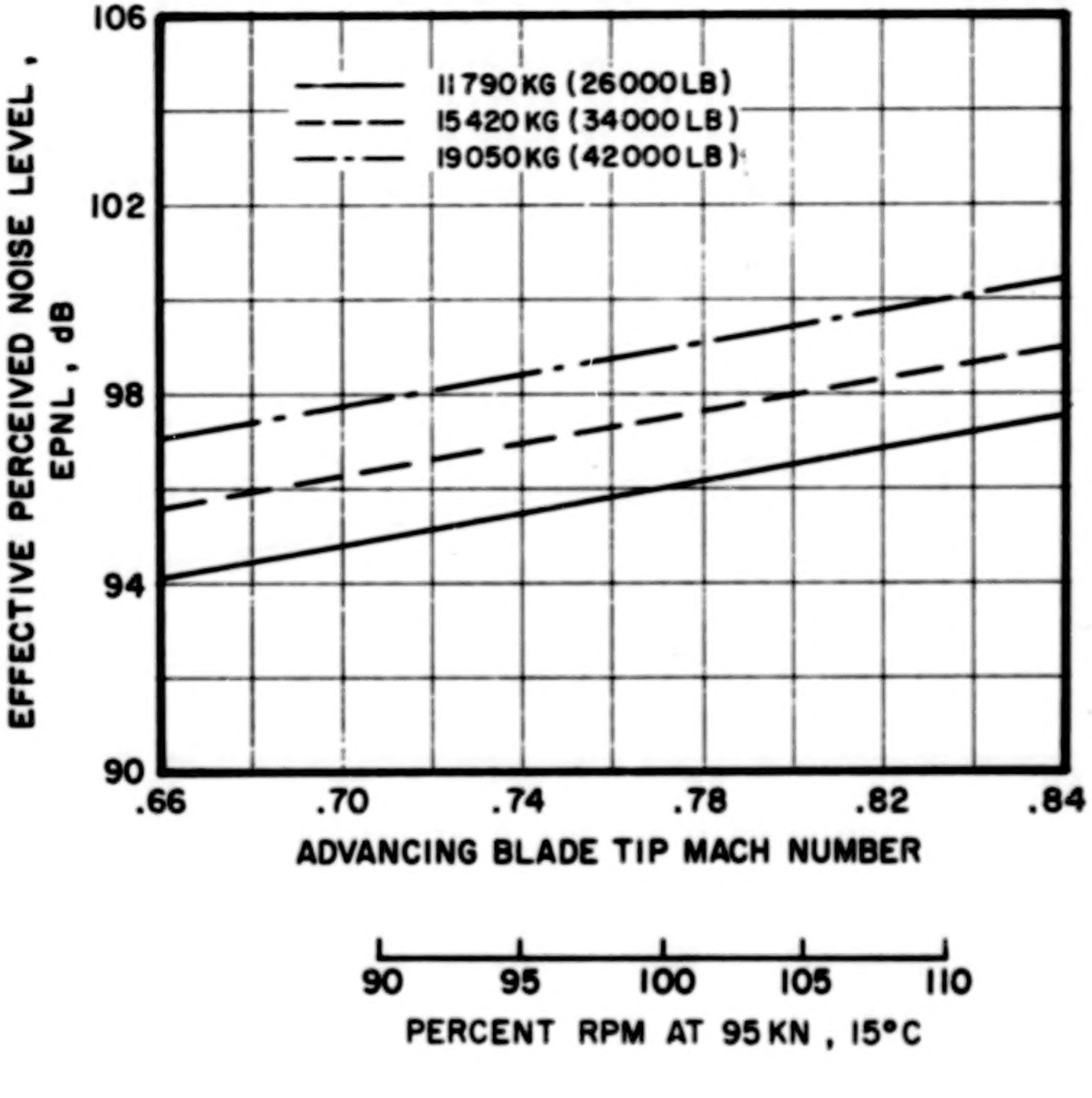


Figure 24. Noise Sensitivity to Tip Mach Number at Six Degree Climb Angle.

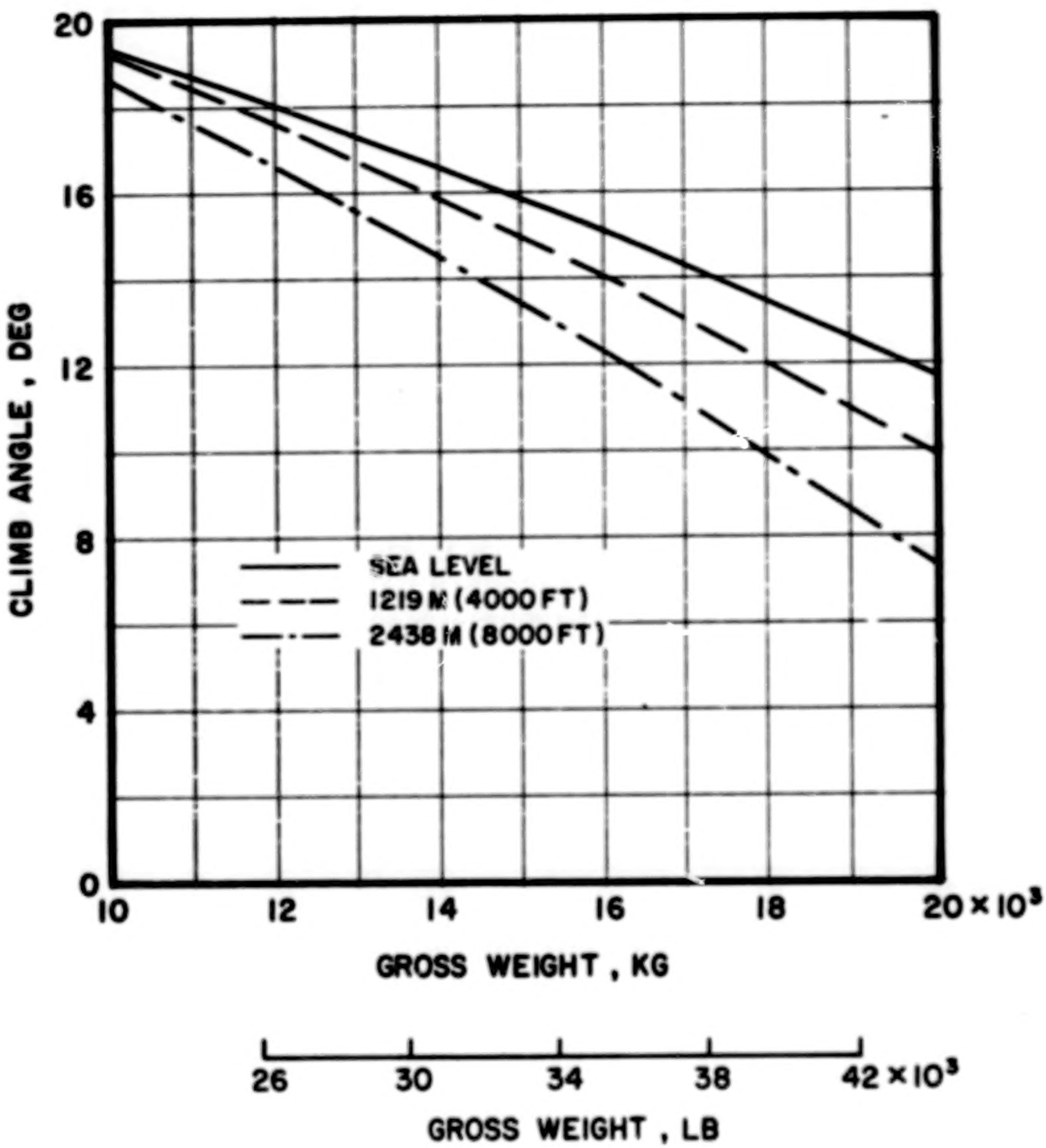


Figure 25. Maximum Achievable Climb Angle at 30-minute Power, Airspeed = 49 m/s (95 kt), ISA.

Landing Noise

The noise produced by the CH-53 during landing descent remains relatively constant for descent angles of up to about six degrees, beyond which it decreases sharply with increasing descent angle (see Figure 26). The peak noise level at six degree descent angle is the result of rotor-wake interaction.

The steepest descent angles are achieved in autorotation. However, autorotation with the collective pitch setting at its lowest position results in high rotor rpm. (At 19050 kg (42000 lb), for example, trim rpm at minimum collective setting is 117 percent.) Descent noise is sensitive to rpm, as shown in Figure 27. The result is that minimum noise is realized at somewhat less than maximum achievable descent angle by increasing collective pitch to reduce rotor rpm. The sensitivity of noise to descent angle and the corresponding trim rpm is shown in Figure 28.

Figure 29 shows the autorotative descent angle for minimum noise as a function of gross weight for several altitude and temperature combinations. A minimum normal rpm of 95 percent is assumed. Because acceptable descent angle may be constrained by passenger comfort or air traffic control criteria, the landing noise minimization program provides for optional input of a specified descent rate and accounts for the appropriate power required to achieve it. Optimum rotor rpm is pre-loaded as a minimum of 100 percent; other values can be optionally input.

Descent angle is redefined in terms of the more readily controlled airspeed and descent rate parameters for output to the pilot.

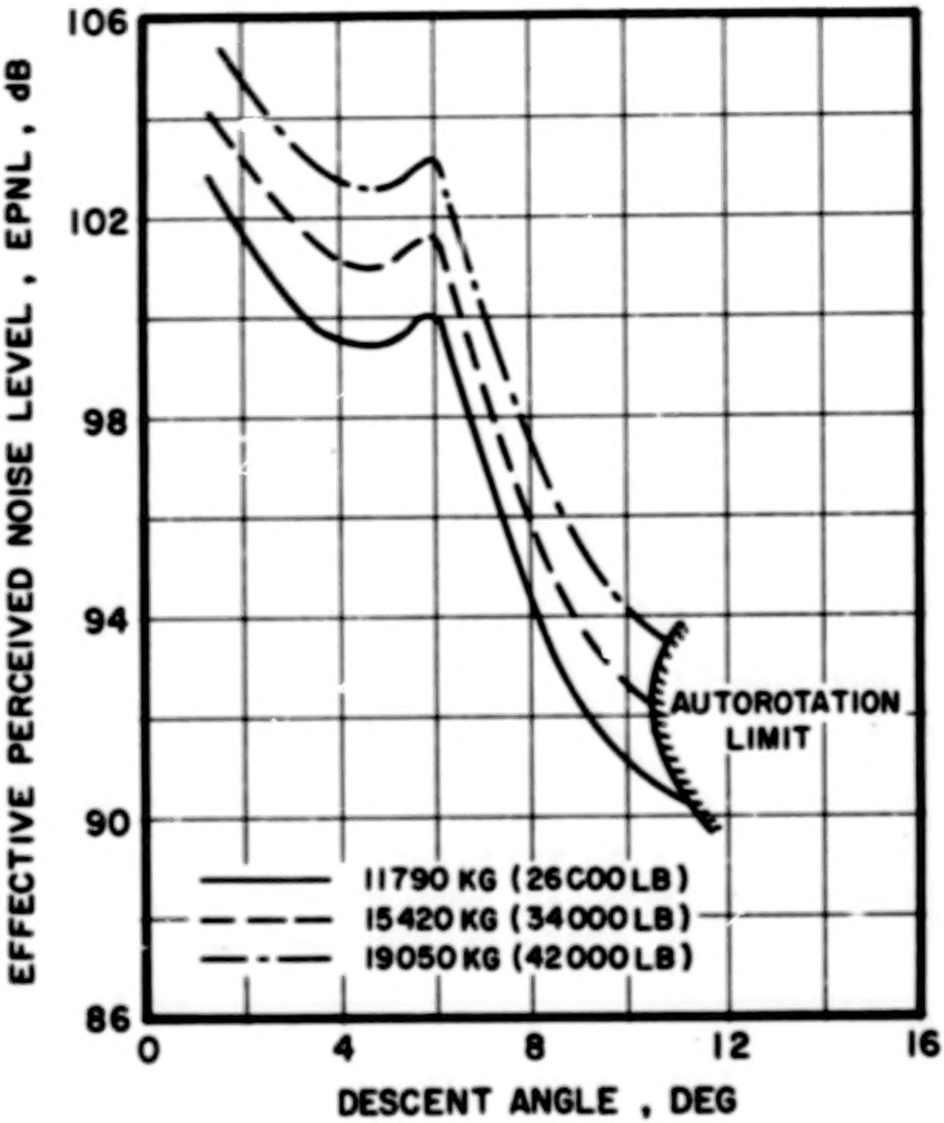


Figure 26. Noise Sensitivity to Descent Angle for Sea Level ISA, Airspeed = 49 m/s (95 kt), 95% rpm, 15°C.

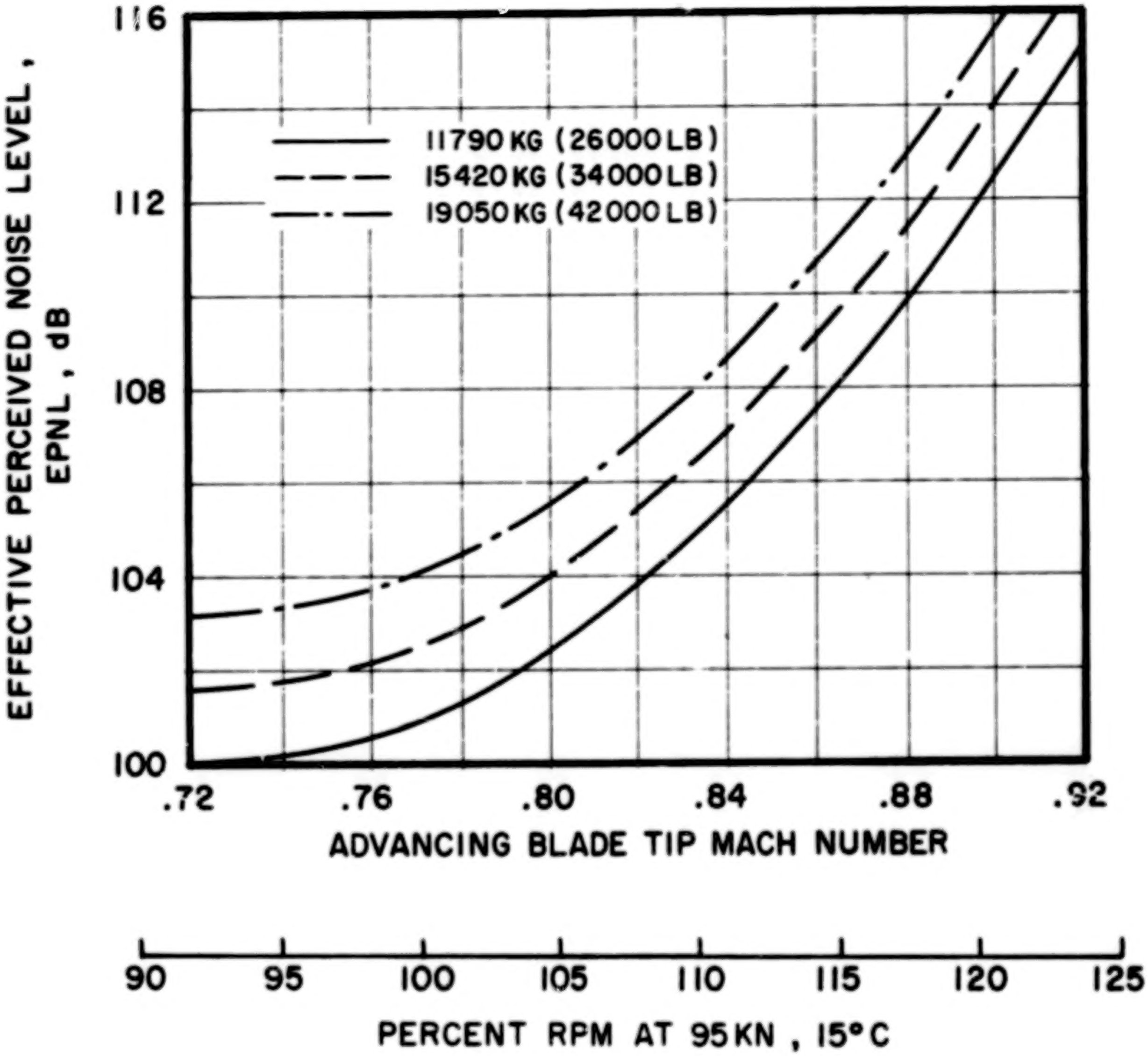
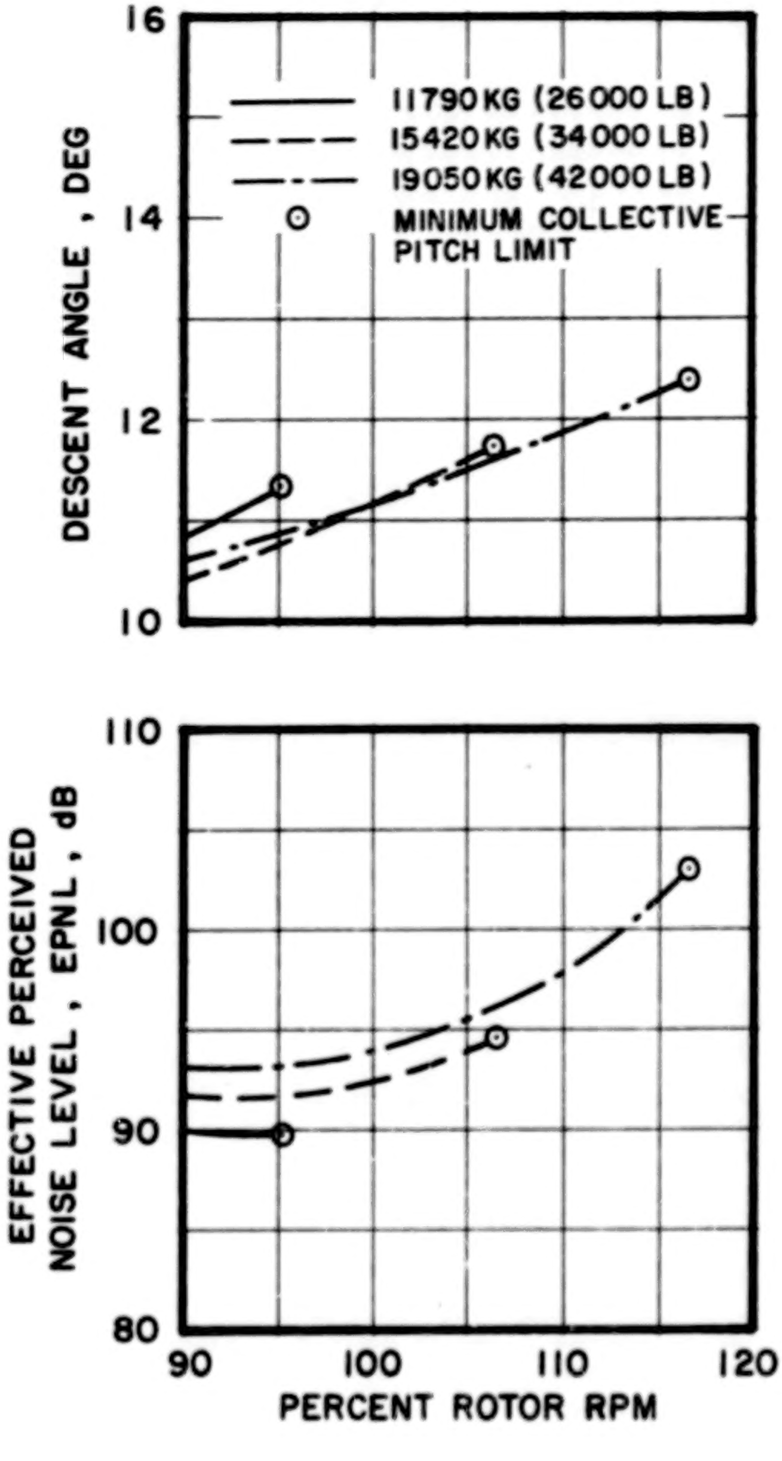
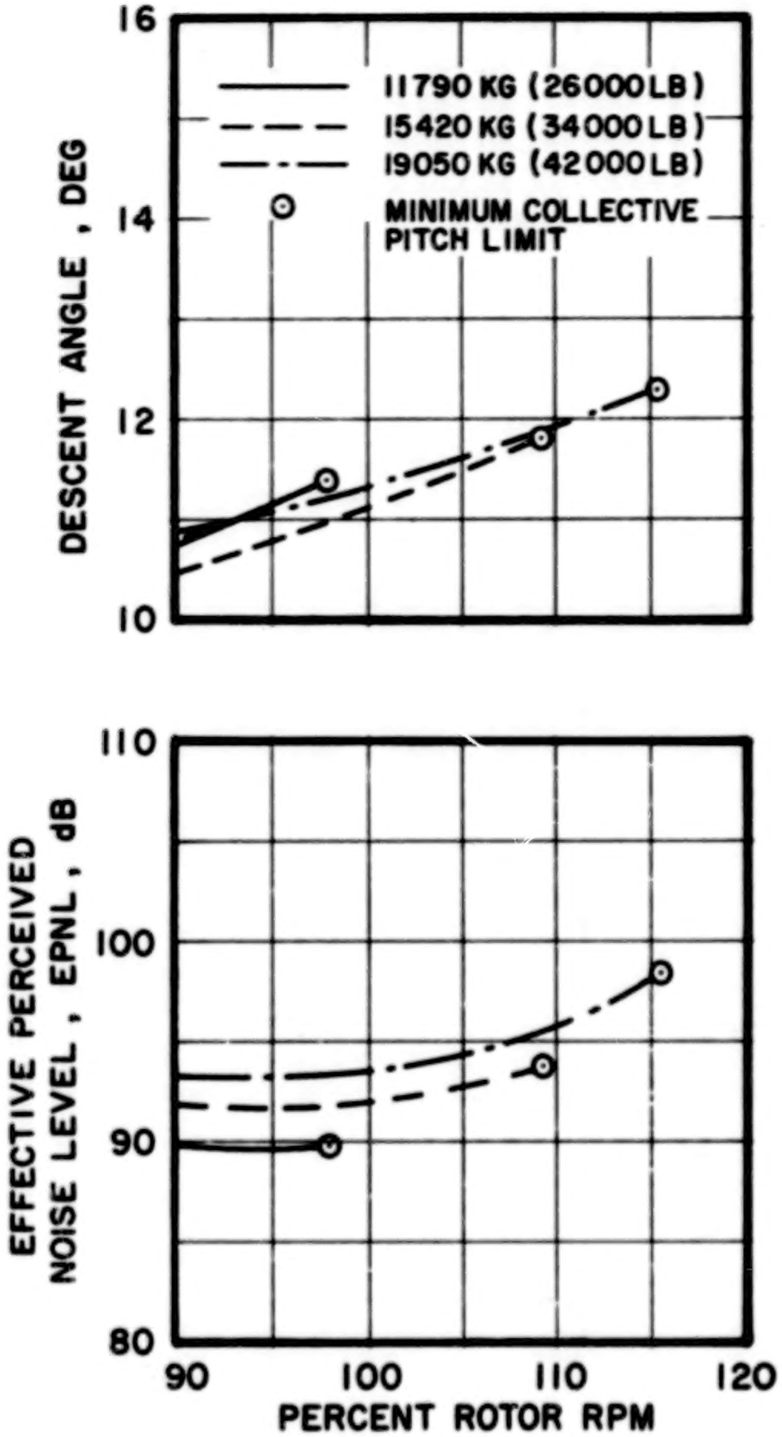


Figure 27. Noise Sensitivity to Tip Mach Number at Six Degree Descent Angle.



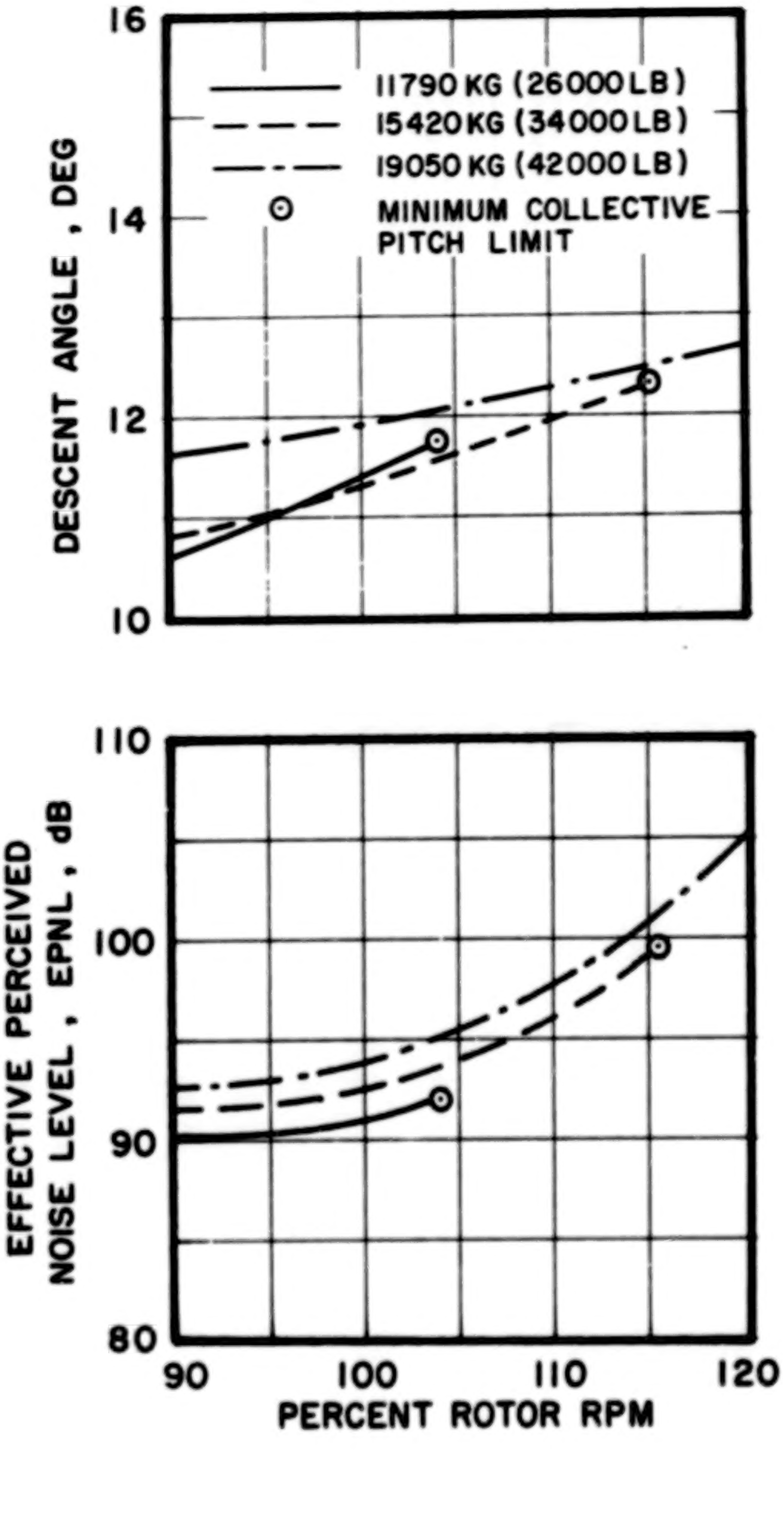
(a) Sea Level ISA

Figure 28. Noise and Descent Angle Sensitivity to Rotor rpm in Autorotation.



(b) Sea Level 35°C

Figure 28. - Continued.



(c) 1829 m (6000 ft) 15°C

Figure 28. - Concluded.

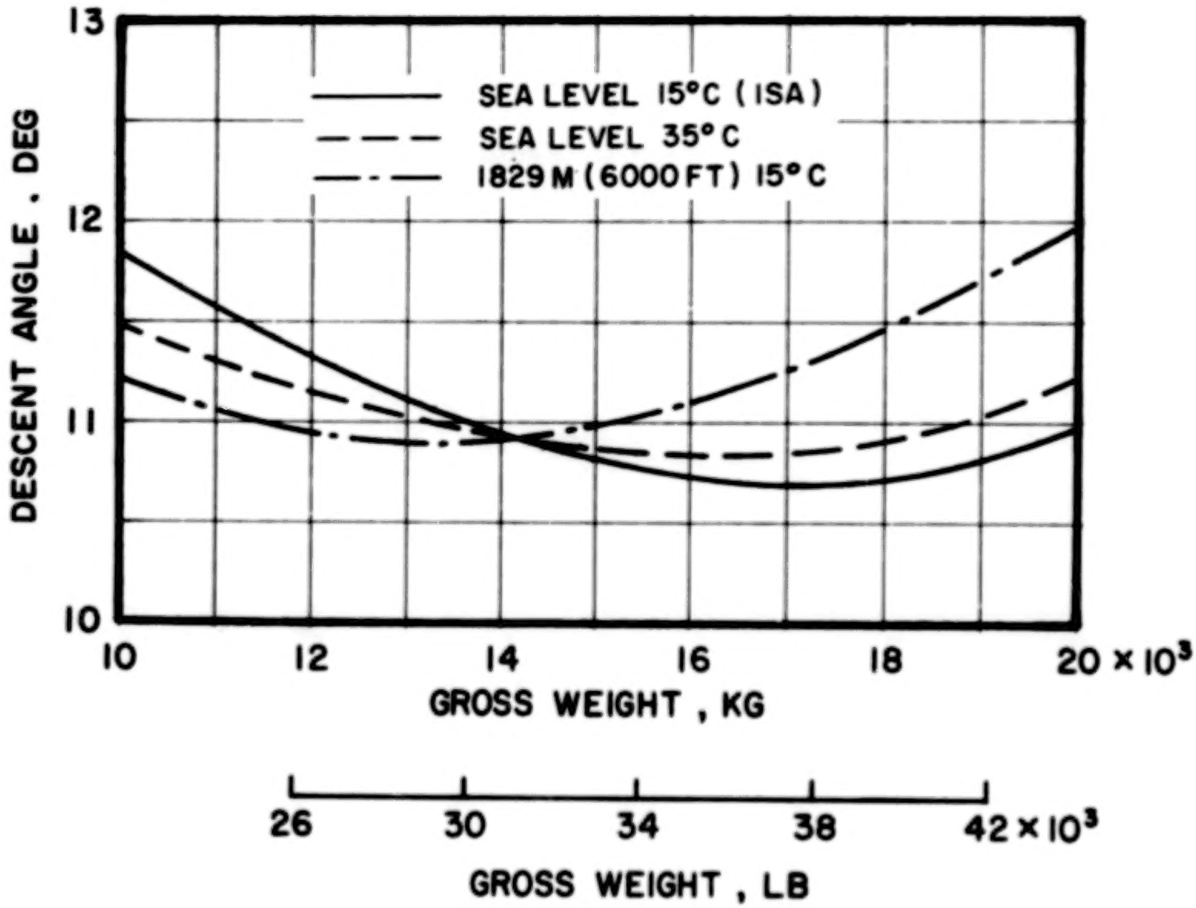


Figure 29. Autorotative Descent Angle for Minimum Noise (95% rpm).

DETAILED PROGRAM DESIGN

The basic design objective of the optimization programs is simplicity of input/output combined with acceptable accuracy. The primary constraint is the 224-step programming capacity of the Hewlett Packard HP-97 computer. These factors resulted in the following design criteria:

1. Subdivision of the overall optimization into eight individual programs, each requiring separate loading into the computer and with its own unique input/output format.

2. Use of curve-fit techniques to model previously calculated performance trends rather than reliance on fundamental analytic methodology.

3. Elimination of variables that have relatively small effect on performance.

The first criterion, division into eight individual programs, permits achievement of a better-than-3-percent accuracy while keeping the input procedures for each program simple and logical. Its drawback is that card manipulation is required to change from one program to another. While constantly improving calculator technology would undoubtedly permit future concentration of all the programs into a single program setup, thereby reducing the requirements for card manipulation, this approach would result in a more complex input/output format to accommodate the same options and variables. Short of a prompting feature, in which an alpha-numeric display could be used to guide the pilot through the operating procedure, such an approach is felt to be less desirable than the one developed for the HP-97.

The second criterion, use of curve-fit techniques to model previously calculated performance trends, greatly reduces the number of program steps and eliminates inputs such as rotor geometry and parasite drag that would be required for a purely analytical approach. Its drawbacks are that it restricts the optimization to a given helicopter model and that configuration variations such as external load drag cannot easily be treated. These drawbacks might be eliminated when a more powerful computer becomes available, but curve fitting is the only practical approach using currently available, low cost computer technology with reasonable program subdivision.

The third criterion, elimination of variables with relatively small effect, minimizes both the programming requirements and the input complexity. An example of an eliminated variable is center of gravity position. As discussed under Assumptions and Limitations, the full CH-53 center of gravity range was found to account for less than a two percent variation in power required, with an even smaller effect on optimum flight conditions. Input variables are limited to gross weight, airspeed, rotor rpm, pressure altitude, temperature, headwind speed, and climb or descent rate.

The eight individual programs, labeled A through H, are listed below with their inputs and outputs. Parentheses indicate optional inputs.

Program	Inputs	Outputs
A. Power Required	GW,ALT,T,TAS(IAS),NR	SHP,Q
B. Fuel Flow	SHP,ALT,T,TAS (IAS), NE, Q, NR	FF
C. Best Range Conditions	GW,(ALT),T(ISA),HWIND	ALT,TAS,IAS,NR
D. Best Range	GW,ALT,T,HWIND	SPR
E. Best Endurance	GW,(ALT),T(ISA)	ALT,TAS,IAS,NR,FF,SPE
F. Maximum Speed	GW,ALT,T(ISA),NR	TAS,IAS
G. Minimum Takeoff Noise	GW,ALT,T,(ROC),(NR)	ROC,TAS,IAS,NR,EPNL
H. Minimum Landing Noise	GW,ALT,T,(ROD),(NR)	ROD,TAS,IAS,NR,EPNL

Seven of the eight programs require the loading of two magnetic cards, one for the program itself (A-1, B-1,..) and the other for the necessary data (A-2, B-2...). The exception is the Best Range Program D, which is complete on a single card. The first (program) card in each case is labeled with input and output locations and is inserted into the face of the computer after loading. The cards are illustrated in Figure 30.

Detailed descriptions of each program, including equations, data constants, and listings, are presented in Appendix I.

User instructions are presented in Appendix II in a stand-alone format that does not require reference to other parts of this report.

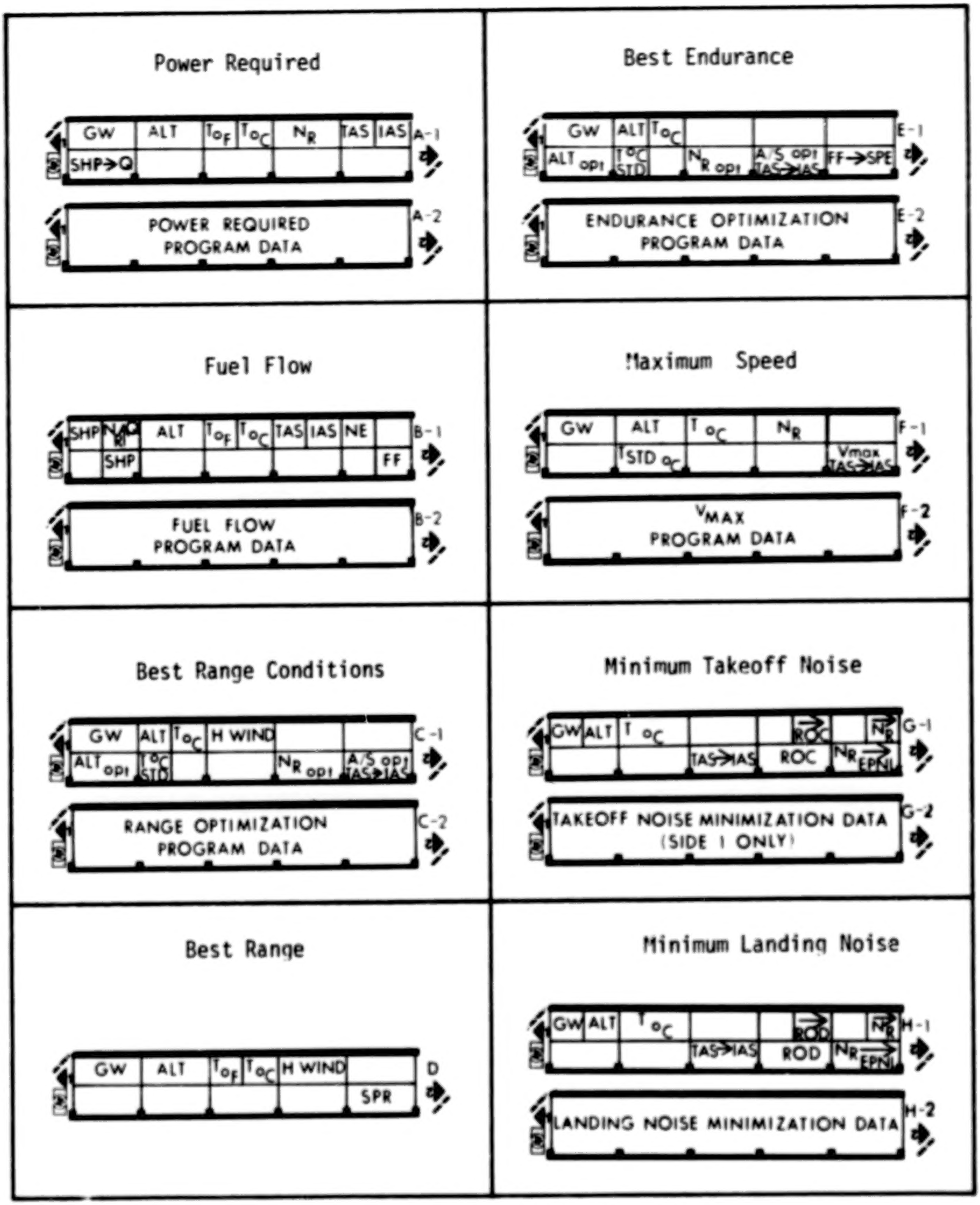


Figure 30. Program Cards.

ACCURACY

Program accuracy is estimated to be generally within three percent. Of this potential error, about half is due to simplifying assumptions in the performance analyses and the other half to curve-fit approximations. The power and fuel flow methodology is generally more accurate than the noise methodology, which is a more recently developed discipline.

A three percent accuracy is more than adequate for the objectives of the optimization programs. Because the optimal operating conditions tend to be maxima or minima on performance trends, the three percent potential error in flight condition generally represents a significantly smaller error in absolute performance. For example, a three percent error in speed for best range (about 2 m/sec or 4 knots) corresponds to only about 1/2 percent error in achieved specific range (see Figure 8).

Accuracy could be improved by expanding the performance methodology or by applying more complex curve-fit techniques. However, the increase in program complexity and user workload that this would entail are not felt to be warranted by an increase in accuracy that probably cannot be matched by pilot input accuracy or control capability.

ASSUMPTIONS AND LIMITATIONS

The performance analyses are subject to simplifying assumptions that are based on a realistic compromise between complexity and accuracy.

No Sensitivity to Center of Gravity

The variance of CH-53 power required between maximum aft and maximum forward center of gravity is less than two percent, varying typically from about one percent at 52 m/sec (100 knots) to 1/2 percent at 77 m/sec (150 knots). For the analysis, the most adverse center of gravity is assumed, consistent with flight manual data.

Constant Parasite Drag

Aside from the variation of drag with speed, which is inherent in the flight test data used to establish the non-dimensional power required, parasite drag is assumed to be constant, representing a given aircraft configuration. The power required to overcome parasite drag accounts for up to 40 percent of total power at high speed. This percentage reduces to about 10 percent at best endurance speed. Therefore, as much as a 10 percent drag change affects total power required by only one to four percent. This tolerance more than covers typical external configuration variation. Obviously for very large drag changes such as for external lift of bulky cargo, the optimization data require modification.

Constant Power Losses

Accessory power requirements consistent with flight manual performance are assumed. No penalty for additional avionics, air conditioning, or anti-icing is assessed. Although potential additional power demands will degrade absolute performance, they will not significantly change the flight conditions for best performance.

No Sidewind Correction

Only headwind and tailwind corrections are accounted for. Sidewinds must be treated by applying their headwind or tailwind component. The effect of wind is limited to its impact on the relationship between airspeed and ground speed.

CH-53 Flight Limitations

The flight limitations of the CH-53 itself must be superimposed on the flight optimization, which is unconstrained. These limitations include the following:

Maximum gross weight = 19,050 kg (42,000 lb)

Maximum ceiling: no absolute limit except as imposed by power or by availability of oxygen equipment.

Maximum sustained airspeed: as defined by Program F.

Allowable rotor rpm variation:

normal: 95 to 105 percent

maximum: 125 percent

minimum: Below 95 percent subject to acceptable degradation of avionics and system torque limitations. Also as may be considered acceptable for recovery following loss of power.

Appendix III discusses the impact of current CH-53 flight limitations on optimum performance.

RESULTS

Programs were developed for use with the Hewlett Packard HP-97 calculator that permit a CH-53 pilot to rapidly determine optimum flight conditions to minimize fuel consumption or takeoff and landing noise.

The improvement in fuel consumption or noise achievable with flight optimization depends on the initial, non-optimum conditions. Typical improvements are shown in the following table:

Typical Fuel Savings for 14512 kg (32000 lb) and ISA Zero Wind

Initial Condition: 77 m/sec (150 kt) at 610 m (2000 ft), 100% N_R

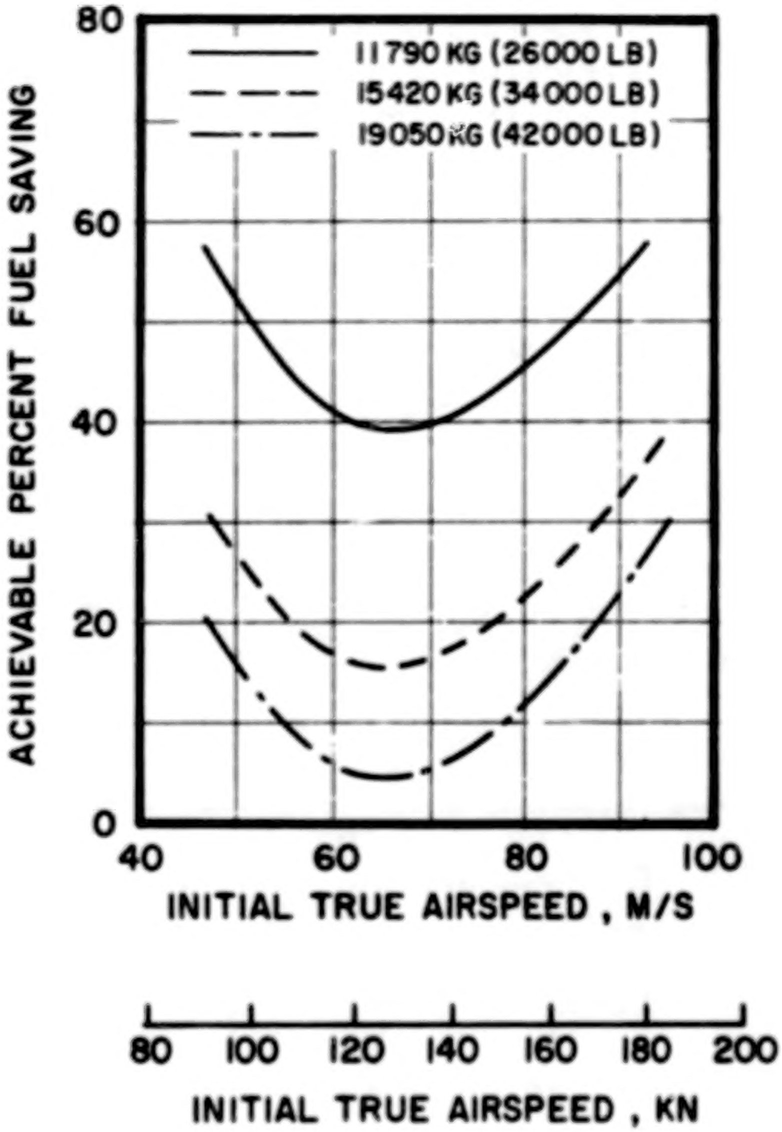
For Given Range:	
Fuel saving from change to best airspeed of 66 m/sec (128 kt)	5%
Fuel saving from change to best altitude of 3932 m (12900 ft)	12%
Fuel saving from change to best rotor rpm of 95%	3%
	20%
For Given Endurance:	
Fuel saving from change to best airspeed of 44 m/sec (86 kt)	32%
Fuel saving from change to best altitude of 3627 m(11900 ft)	8%
Fuel saving from change to best rotor rpm of 96%	1%
	41%

As shown, for the initial conditions assumed, a 20% fuel saving for given range and a 41% fuel saving for given endurance are achievable with flight optimization. Most of these savings result from airspeed and altitude optimization, with the last few percent contributed by rotor rpm tuning.

Fuel savings achievable as a function of initial flight conditions are shown in Figure 31 for ISA and zero wind. At light gross weight and initially high speed, savings of over 50 percent can be realized.

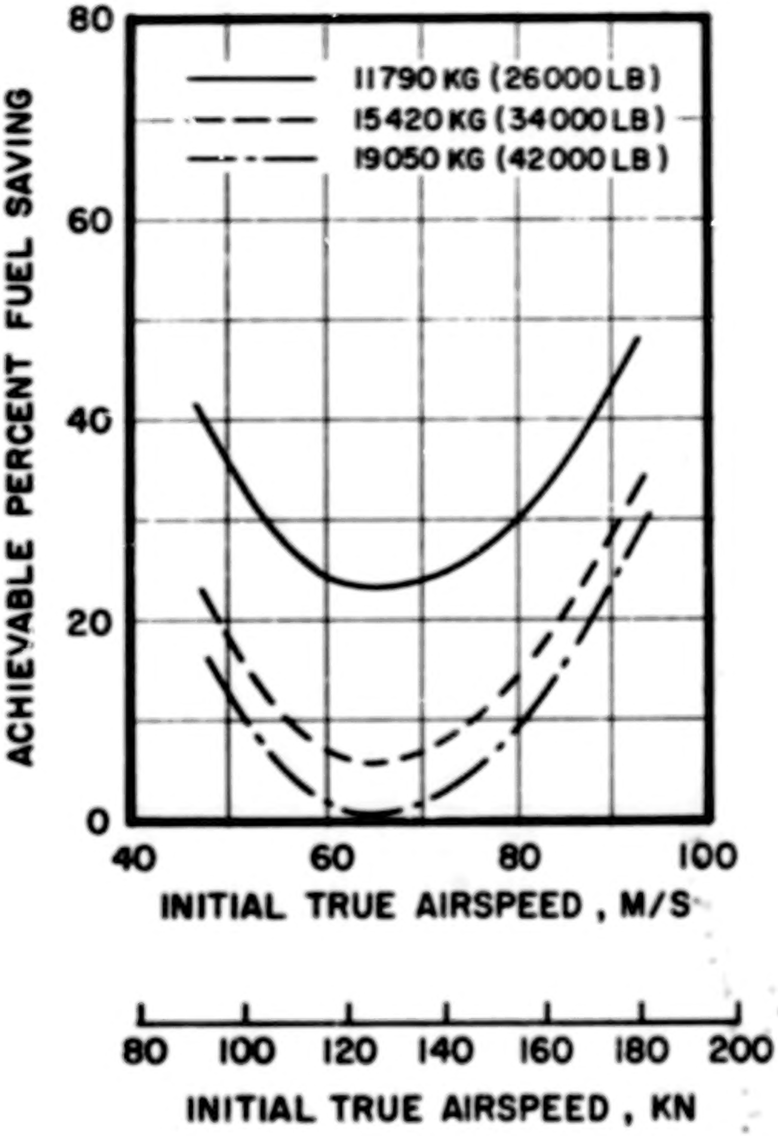
At the same typical gross weight of 14512 kg (32000 lb), takeoff noise can be reduced by seven dB EPNL by climbing at optimum rotor speed and climb angle compared to a typical six degree climb at 100% rpm. Compared to a six degree descent angle at 100% rpm, landing noise can be reduced by eleven dB EPNL at optimum rpm and descent angle.

Noise reduction achievable as a function of initial flight conditions is shown in Figure 32.



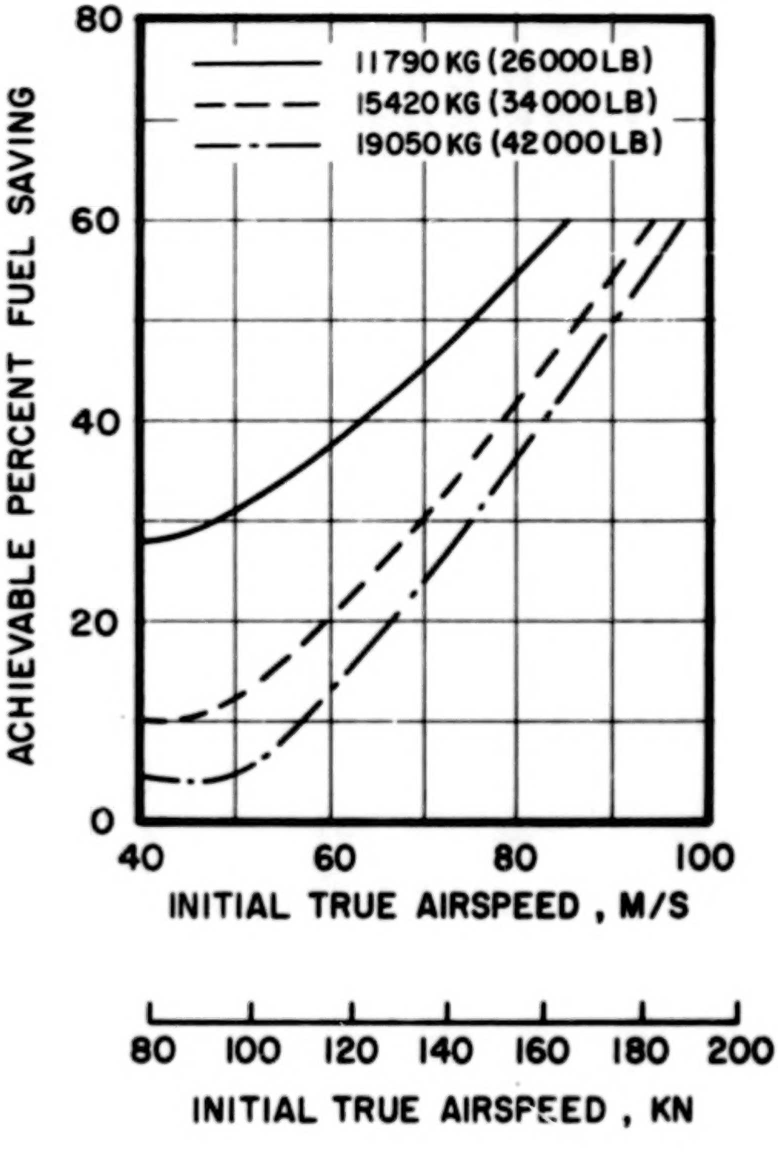
(a) Fixed Range, Sea Level

Figure 31. Achievable Fuel Saving as a Function of Initial Conditions (Zero Wind, ISA, 100% Initial rpm).



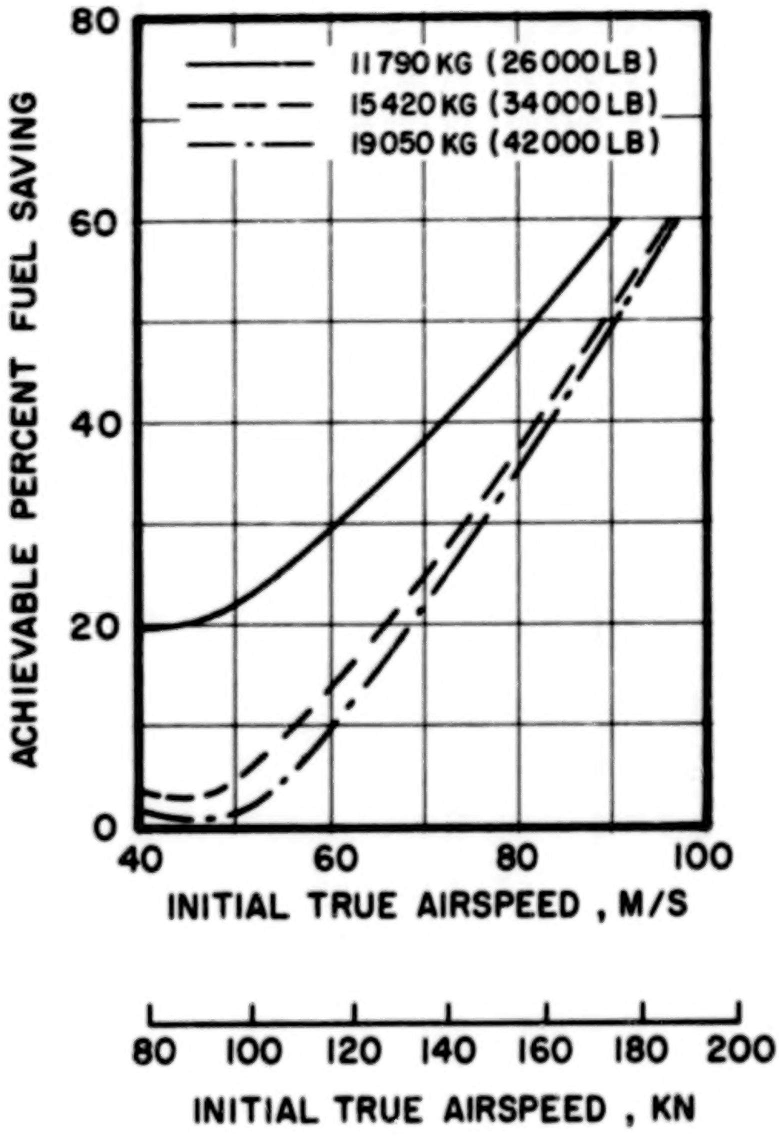
(b) Fixed Range, 1524 m (5000 ft)

Figure 31. - Continued.



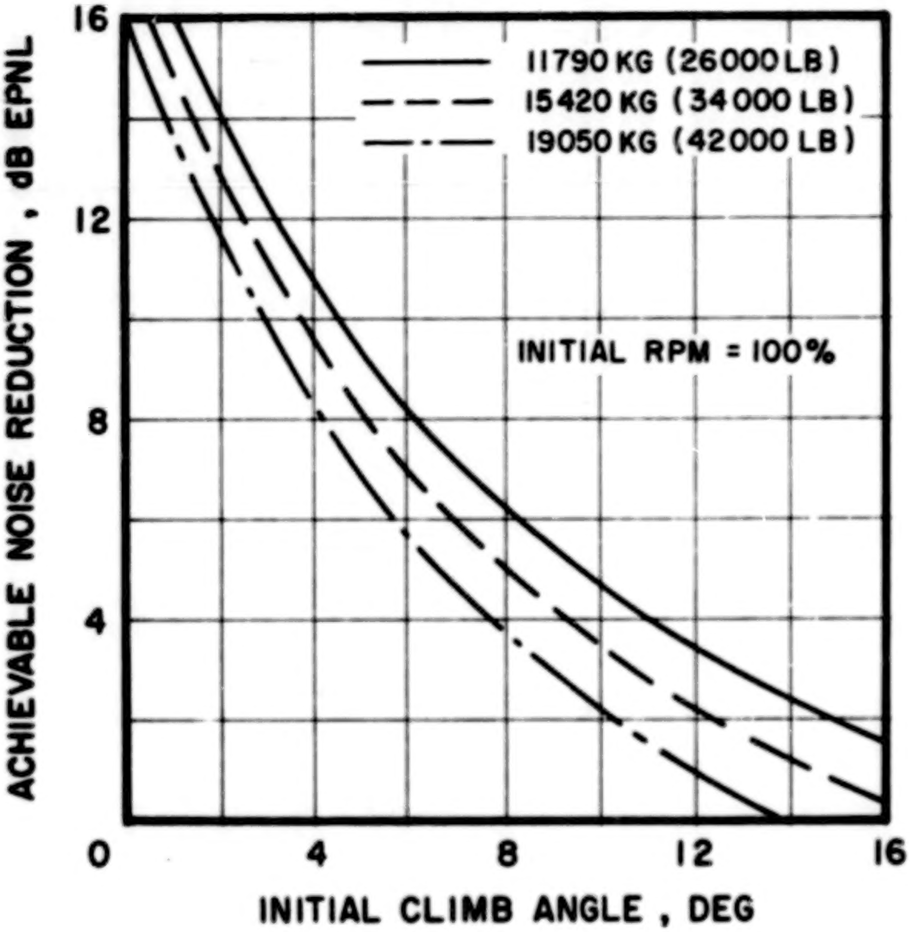
(c) Fixed Endurance, Sea Level

Figure 31. - Continued.



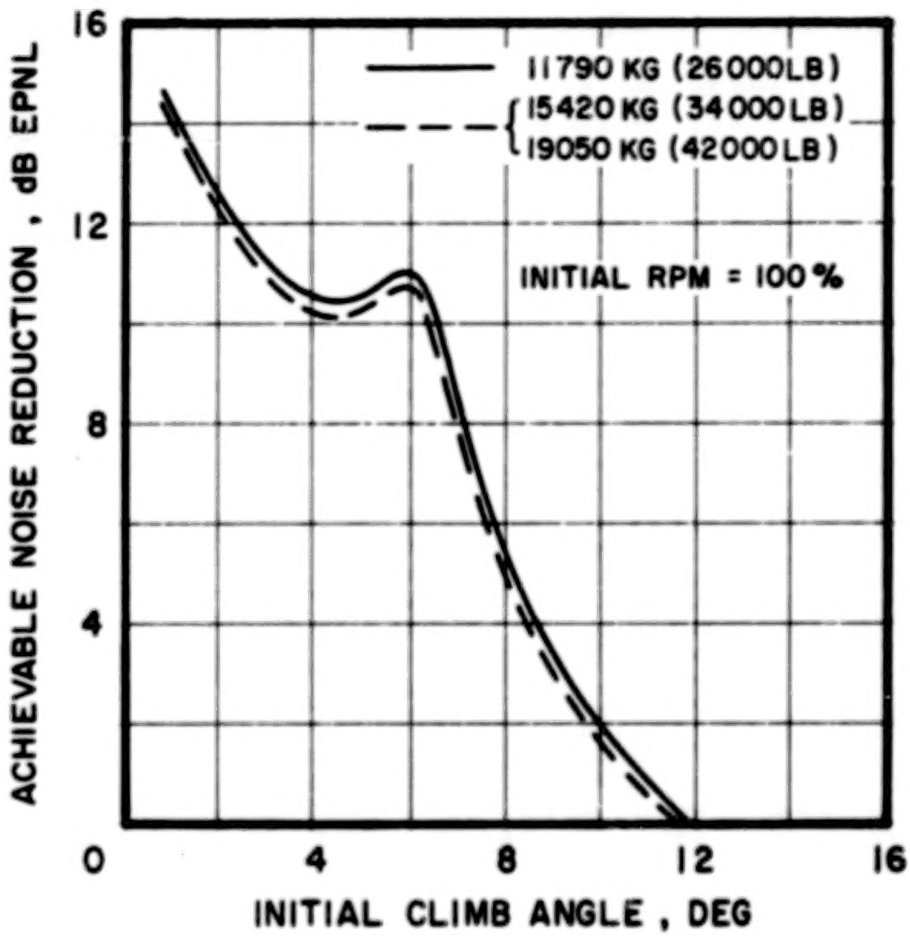
(d) Fixed Endurance, 1524 m (5000 ft)

Figure 31. - Concluded.



(a) Takeoff

Figure 32. Achievable Takeoff and Landing Noise Reduction as a Function of Initial Conditions (Sea Level ISA).



(b) Landing

Figure 32. - Concluded.

CONCLUSIONS

Currently available, low-cost computer technology can be used to provide a helicopter pilot with the information necessary to achieve significant cruise fuel savings and takeoff and landing noise reduction. For a nominal set-up and input, the pilot is provided with optimum airspeed, altitude, and rotor rpm for minimum fuel consumption, and optimum climb or descent rate and rotor rpm for minimum noise. Depending on initial conditions, up to 50 percent fuel savings and ten dB EPNL noise reductions can be achieved.

The computer programs developed in this study demonstrate the feasibility of a cockpit computer approach to flight optimization. However, the inherent limitations of the HP-97 make some of the required pilot manipulations more cumbersome than may be acceptable in a production system. These limitations will largely disappear with the availability of fast-developing small computer technology.

RECOMMENDATIONS

The feasibility of applying available, low-cost hand-held computer technology to help a helicopter pilot optimize performance has been established. However, the limitations of the HP-97 computer impose some penalties in user input redundancy and card manipulation that can be eliminated with the availability of fast-developing hand-held computer technology. In addition, this technology will permit expansion of the optimization to other performance categories and applications. Refinements that warrant further study include:

- Adaptation to more advanced hand-held computer technology to simplify user input, including potential use of automatic prompting.
- Expansion to include performance categories such as hover and climb optimization.
- Automated input of selected parameters such as ambient temperature and pressure altitude.
- Optimization to maximize dynamic component lives.
- Optimization to minimize vibration.
- Expanded noise optimization to include wind effects and footprint characteristics.
- Addition of navigation options to optimize point-to-point operation.

Most important, prototype systems should be placed in the hands of helicopter pilots for evaluation. Their feedback should be used to incorporate desirable changes in the prototypes before commitment to large-scale operational status.

REFERENCES

1. Edge, P. M. and Cawthorn, J. M., "Selected Methods for Quantification of Community Exposure to Aircraft Noise," NASA Technical Note TN D-7977, February, 1976.

2. Munch, C. L., "Prediction of V/STOL Noise for Application to Community Noise Exposure," Report No. DOT-TSC-OST-73-19, May, 1973.

APPENDIX I. DETAILED PROGRAM DESCRIPTION

This Appendix presents the equations, data constants, and listings for each of the eight optimization programs. This information is sufficient to permit reprogramming from scratch or to incorporate desired program modifications. Unless otherwise specified, parameters are in customary rather than SI units.

For detailed programming instructions, the reader should refer to the Hewlett Packard HP-97 manual.

STANDARD EQUATIONS USED IN HP-97 PROGRAMS

Temperature Conversion	$T\ (^{o}F) = 1.8 * T\ (^{o}C) + 32.$
Standard Temperature	$T_{STD}\ ^{o}F = 59. - .00356 * ALT$
	$T_{STD}\ ^{o}C = 15. - .00198 * ALT$
Density Ratio	$\frac{\rho}{\rho o} = \left(\frac{459.7 + 59}{459.7 + T^{o}F}\right) \left(1 - \frac{h_p}{145366}\right)^{5.256}$
	or $= \left(\frac{273.2 + 15}{273.2 + T^{o}C}\right) \left(1 - \frac{h_p}{145366}\right)^{5.256}$
True Airspeed	$TAS = \underbrace{(8.0 + .914286 * IAS)}_{CAS} (\rho o/\rho)^{1/2}$
Speed of Sound	$C = 49.04\ (459.7 + T^{o}F)^{1/2}$
Tip Speed	$\Omega R = 700. * \frac{\%\ N_R}{100}$
Tip Mach Number	$M_t = \frac{\Omega R\ (+\ Vfps)}{C}$

POWER REQUIRED PROGRAM EQUATIONS

Advance Ratio $\mu = \frac{TAS * 1.687}{\Omega R}$

Nondimensional Gross Weight

$$C_W = \frac{GW}{\pi R^2 \rho (\Omega R)^2} = \frac{GW}{4094.16 \rho (\Omega R)^2}$$

Power Coefficient

$$Cp = .0001473 + .0002462 \mu + .002733 \mu^2$$
$$+ .04554 C_W + 5.892 C_W^2 - .6969 \mu C_W + 1.339 \mu^2 C_W$$

Compressibility Correction

$$KC = 1 + 200. [\mu^{1/3} M_t^3 C_W^{.07} - .110]^{2.13}$$

Tail Rotor Correction

$$KTR = 1.3634 - 12.31 C_W - .9245 \mu + 35.06 \mu C_W$$

Power Required

$$SHP = [(Cp \quad) (KC) (KTR) (\frac{\pi R^2 \rho (\Omega R)^3}{550}) + 147.] \frac{1}{.995}$$

$$= 7.4813 [(Cp \quad) (KC) (KTR) (\rho) (\Omega R)^3 \quad] + 148.$$

Torque

$$Q = SHP/(0.64*N_R)$$

POWER REQUIRED PROGRAM STORAGE REGISTER CONTENTS

	Primary		Secondary		
0	.002378	10	.0001473	A	C_W
1	459.7	11	.0002452	B	ρ
2	hp	12	.002733	C	T
3	KC	13	.04554	D	ΩR
4	7.481325	14	5.892	E	μ
5	GW	15	-.6969	I	$\frac{\rho}{\rho_o}$, Cp , SHP
6	145366.	16	1.339		
7	.914286	17	1.3634		
8	4094.16	18	-12.31		
9	TAS	19	-.9245		

```
001  *LBL A      Store and print inputs
002  STO 6
003  [illegible]
004  [illegible]
005  *LBL B
006  STO 2
007  PRTX
008  RTN
009  *LBL C      Convert °C to °F
010  1
011  .
012  8
013  ×
014  3
015  2
016  +
017  *LBL C
018  STO C
019  PRTX
020  RTN
021  *LBL D
022  PRTX
023  7
024  ×
025  STO D
026  RTN
027  *LBL e      Convert IAS to TAS
028  RCL 7
029  ×
030  8
031  +
032  STO 9
033  GSB 1
034  1/X
035  √X
036  RCL 9
037  ×
038  *LBL E
039  STO 9
040  PRTX
041  RTN
042  *LBL 1      Calculate σ/σ0
043  1
044  RCL 2
045  RCL 6
046  ÷
047  -
048  5
049  .
050  2
051  5
052  6
053  y^x
054  5
055  9
056  RCL 1
057  ÷
058  LSTX
059  RCL C
060  +
061  ÷
062  ×
063  STO 1
064  RTN
065  *LBL a      Calculate advance ratio
066  GSB 1
067  RCL 0
068  ×
069  STO 8
070  RCL 9
071  1
072  .
073  6
074  8
075  7
076  ×
077  RCL D
078  ÷
079  STO E
080  RCL 5      Calculate C_W
081  RCL 8
082  ÷
083  RCL 8
084  ÷
085  RCL D
086  x²
087  ÷
088  STO A
089  RCL C      Calculate M_t
090  RCL 1
091  +
092  √X
093  4
094  9
095  .
096  0
097  4
098  ×
099  RCL D
100  x≷y
101  ÷
102  3          Calculate compressibility correction factor KC
103  y^x
104  RCL E
105  .
106  3
107  3
108  3
109  y^x
110  ×
111  RCL A
112
113  0
114  [illegible]
115  [illegible]
116  ×
117  .
118  1
119  1
120  .
121  [illegible]
122  0
123  ENT↑
124  2
125  .
126  1
127  3
128  [illegible]
129  2
130  0
131  [illegible]
132  ×
133  1
134  +
135  STO 0
136  R/S        Calculate Cp
137  RCL 0
138  RCL 1
139  RCL E
140  ×
141  +
142  RCL 2
143  RCL E
144  x²
145  ×
146  +
147  RCL 3
148  RCL A
149  ×
150  +
151  RCL 4
152  RCL A
153  x²
154  ×
155  +
156  RCL 5
157  RCL E
158  ×
159  RCL A
160  ×
161  +
162  RCL 6
163  RCL E
164  x²
165  ×
166  RCL A
167  ×
168  +
169  STO I
170  RCL 7      Calculate tail rotor correction
171  RCL 8
172  RCL A
173  ×
174  ×
175  RCL 9
176  RCL E
177  ×
178  +
179  R/S
180  3
181  5
182  .
183  0
184  6
185  RCL A
186  ×
187  RCL C
188  ×
189  +
190  RCL 3      Calculate SHP
191  ×
192  RCL 1
193  ×
194  RCL 8
195  ×
196  RCL D
197  3
198  y^x
199  ×
200  RCL 4
201  ÷
202  1
203  4
204  0
205  ÷
206  PRTX
207  STO I
208  RCL D      Calculate torque
209  7
210  ÷
211  .
212  6
213  4
214  ×
215  ÷
216  PRTX
217  RTN
```

Power Required Program Listing

FUEL FLOW PROGRAM EQUATIONS

Uncorrected Fuel Flow

$$FF_0 = [374.9 + .002506\ ALT - .1778x10^{-5}\ ALT^2 + .64x10^{-10}\ ALT^3]$$

$$+ [.3193 - .1525x10^{-4}\ ALT + .1949x10^{-8}\ ALT^2 - .6833x10^{-13}\ ALT^3]\ x\ \frac{SHP}{NE}$$

$$+ [.1171x10^{-4} + .4164x10^{-8}\ ALT - .4926x10^{-12}\ ALT^2 + .1956x10^{-16}\ ALT^3]\ x\ \frac{SHP}{NE}^2$$

$$+ [.2635 - .333x10^{-4}\ ALT\ (ALT \leq 4950)\ \text{ or }\ .097\ (ALT > 4950)]\ x\ T$$

$$+ [.1354x10^{-3} + .1399x10^{-7}\ ALT - .8309x10^{-12}\ ALT^2 + .1773x10^{-16}\ ALT^3]\ x\ T\ x\ \frac{SHP}{NE}$$

Airspeed Correction

$$KAS = 1.0 - .25x10^{-4}\ TAS - .6238x10^{-6}\ TAS^2$$

Total Fuel Flow

$$FF = FF_0\ x\ KAS\ x\ NE$$

FUEL FLOW PROGRAM STORAGE REGISTER CONTENTS

	Primary		Secondary		
0	FF	10	$.1949 \times 10^{-8}$	A	SHP
1	0.0	11	$-.6833 \times 10^{-13}$	B	hp
2	$-.333 \times 10^{-4}$	12	$.1171 \times 10^{-4}$	C	T
3	4950.	13	$.4164 \times 10^{-8}$	D	TAS
4	374.9	14	$-.4926 \times 10^{-12}$	E	NE
5	$.2506 \times 10^{-2}$	15	$.1956 \times 10^{-16}$	I	
6	$-.1778 \times 10^{-5}$	16	$.1354 \times 10^{-3}$		
7	$.64 \times 10^{-10}$	17	$.1399 \times 10^{-7}$		
8	.3193	18	$-.8309 \times 10^{-12}$		
9	$-.1525 \times 10^{-4}$	19	$.1773 \times 10^{-16}$		

Calculate SHP

```
*LBLa
X⇄Y
PRTX
X⇄Y
PRTX
x
.
6
4
x
```

Store and print inputs

```
*LBLA
STOA
PRTX
RTN
*LBLB
STOB
PRTX
RTN
*LBLc
```

Convert °C to °F

```
1
.
8
x
3
2
+
```

```
*LBLC
STOC
PRTX
RTN
```

Convert IAS to TAS

```
*LBLd
.
9
1
4
3
x
8
+
STOD
1
RCLB
1
4
5
7
6
6
÷
-
5
.
2
5
6
Y^x
5
9
ENT↑
4
5
9
.
7
+
LSTX
RCLC
+
÷
x
1/X
√X
RCLD
x
```

```
*LBLD
STOD
PRTX
RTN
*LBLE
STOE
PRTX
RTN
```

Calculate FF_0

```
*LBLe
RCLA
RCLE
+
STOA
RCLB
RCL3
X≠Y?
GTO1
R↓
RCL2
x
.
2
6
3
5
+
GTO3
*LBL1
.
Ø
9
7
*LBL3
RCLC
x
STOØ
4
GSB2
ST+Ø
8
GS[illegible]
[illegible]
x
ST+Ø
1
2
GSB2
RCLA
X²
x
ST+Ø
1
6
GSB2
RCLA
x
RCLC
x
ST+Ø
RCLA
RCLE
ST×Ø
x
STOA
```

Calculate airspeed correction

```
.
6
2
3
8
EEX
CHS
6
RCLD
X²
x
CHS
.
2
5
EEX
CHS
4
RCLD
x
+
1
+
ST×Ø
RCLØ
PRTX
RTN
```

Polynomial evaluation subroutine

$SUM = A + Bx + Cx^2 + Dx^3$

x = Altitude

```
*LBL2
STOI
R↓
RCLi
ISZI
RCLi
RCLB
x
+
ISZI
RCLi
RCLB
X²
x
+
ISZI
RCLi
RCLB
3
Y^x
x
+
RTN
```

Fuel Flow Program Listing

RANGE OPTIMIZATION PROGRAM EQUATIONS

Optimal Altitude

$$ALT_{OPT} = 35937.5 - .71875\ GW$$

Optimal Rotor RPM

$$NR_{OPT} = [-422.2 + .02595\ GW - .3264 \times 10^{-6}\ GW^2]$$
$$+ [52.68 - .002618\ GW + .3297 \times 10^{-7}\ GW^2] \times \ln(ALT + 4000)$$
$$+ .09722\ (T - 59.)$$

Optimal Airspeed (No Wind)

$$V_{OPT} = [121.13 + .11222\ T] \times e^{[.1145 \times 10^{-5} + .3664 \times 10^{-9}\ T - .9767 \times 10^{-11}\ T^2 + .3708 \times 10^{-12}\ T^3] \times ALT}$$

Headwind Correction

$$\Delta V_{HW} = V_{WIND} \times [.8426 - .1166 \times 10^{-4}\ GW] \times e^{[-.59 \times 10^{-4} + .10188 \times 10^{-8}\ GW] \times ALT}$$

Tailwind Correction

$$\Delta V_{TW} = V_{WIND} \times [.6118 - .80125 \times 10^{-5}\ GW] \times e^{[-.4137 \times 10^{-4} + .5144 \times 10^{-9}\ GW] \times ALT}$$

Corrected Optimal Airspeed

$$A/S_{OPT} = V_{OPT} + \Delta V$$

RANGE OPTIMIZATION PROGRAM STORAGE REGISTER CONTENTS

	Primary		Secondary		
0	N_R	10	-.002618	A	GW
1	TAS	11	52.68	B	ALT
2	$.1145\times10^{-5}$	12	$-.1166\times10^{-4}$	C	T
3	$.3664\times10^{-9}$	13	.8426	D	WIND
4	$-.9767\times10^{-11}$	14	$.10188\times10^{-8}$	E	Intermediate Values
5	$.3708\times10^{-12}$	15	$-.59\times10^{-4}$	I	
6	-.71875	16	$-.80125\times10^{-5}$		
7	35937.5	17	.6118		
8	.02595	18	$.5144\times10^{-9}$		
9	-422.2	19	$-.4137\times10^{-4}$		

```
*LBLA
STOA      Store and print inputs
PRTX
6         Calculate optimal
GSB1      altitude
PRTX
RTN
*LBLB
STOB
PRTX
.
0
0         Calculate T_STD
1
9
8
x
CHS
1
5
+
RTN
*LBLb
1         Convert °C to °F
.
8
x
3
2
+
STOC
PRTX
RTN
*LBLC
PRTX
STOD
RTN
*LBLD
8
GSB1      Calculate optimal N_R
RCLA
x²
3
2
5
4
EEX
CHS
1
0
x
-
STOE
1
0
GSB1
RCLA
x²
3
2
9
7
EEX
CHS
1
1
x
+
RCLB
4
EEX
3
+
LN
x
RCLE
+
RCLC
5
9
-
.
0
9
7
2
2
x
+
PRTX
STO0
RTN
*LBLE
0
STOE      Calculate wind corrections
RCLD
X=0?
GTO2
X<0?
GTO3
1
2
GSB1
x
1
4
GTO4
*LBL3
1
6
GSB1
x
1
8
*LBL4
GSB1
RCLA
x
e^x
x
STOE
*LBL2
RCLC      Calculate optimal TAS
3
y^x
RCL5
x
RCLC
x²
RCL4
x
+
RCLC
RCL3
x
+
RCL2
+
RCLB
x
e^x
RCLC
.
1
1
2
2
2
x
1
2
1
.
1
3
+
x
RCLE
+
PRTX
STO1
1         Convert TAS to IAS
RCLB
1
4
5
3
6
6
÷
-
5
.
2
5
6
y^x
5
9
ENT↑
4
5
9
.
7
+
LSTX
RCLC
+
÷
x
√x
RCL1
x
8
-
.
9
1
4
2
8
6
+
STOE
PRTX
RTN
*LBL1
STOI      Polynomial evaluation
R↓        subroutine
RCLA
RCL1
x         SUM = A + Bx
ISZI
RCL1      x = Gross Weight
+
RTN
```

Range Optimization Program Listing

BEST RANGE PROGRAM EQUATIONS

Uncorrected Specific Range

$$SPR_o = .09436 + .4198 x 10^{-5} ALT + .31 x 10^{-10} ALT^2$$

$$- .8154 x 10^{-6} GW - .7651 x 10^{-10} ALT\ GW - .2966 x 10^{-14} ALT^2\ GW$$

Wind Correction

$$\Delta SPR_V = \frac{Vwind}{20.} x [.01529 + .3935 x 10^{-6} ALT + .1864 x 10^{-10} ALT^2$$

$$- .1405 x 10^{-6} GW - .5359 x 10^{-11} ALT\ GW - .837 x 10^{-15} ALT^2\ GW]$$

Temperature Correction

$$\Delta SPR_T = (\frac{59. - T}{36.}) x [-.0023 + .5469 x 10^{-7} GW$$

$$+ .301 x 10^{-3} e^{.000122\ ALT}]$$

Best Specific Range

$$SPR = SPR_o + \Delta SPR_V + \Delta SPR_T$$

BEST RANGE PROGRAM STORAGE REGISTER CONTENTS

Primary		Secondary			
0	0.0	10	0.0	A	GW
1		11		B	ALT
2		12		C	T
3		13		D	WIND
4		14		E	SPR
5		15		I	
6		16			
7		17			
8		18			
9	0.0	19	0.0		

Store and print inputs

```
*LBLA
PRTX
STOA
RTN
*LBLB
PRTX
STOB
RTN
```

Convert °C to °F

```
*LBLc
1
.
8
×
3
2
+
```

```
*LBLC
PRTX
STOC
RTN
*LBLD
PRTX
STOD
RTN
```

Calculate SPR_0

```
*LBLE
.
0
9
4
3
6
RCLB
4
1
9
8
EEX
CHS
9
×
+
RCLB
x²
3
1
EEX
CHS
1
2
×
+
RCLA
8
1
5
4
EEX
CHS
1
0
×
-
RCLA
RCLB
×
7
6
5
1
EEX
CHS
1
4
×
-
RCLB
x²
RCLA
×
2
9
6
6
EEX
CHS
1
8
×
-
STOE
```

Calculate ΔSPR_V,

head/tail wind correction

```
.
0
1
5
2
9
RCLB
3
9
3
5
EEX
CHS
1
0
×
+
RCLB
x²
1
8
6
4
EEX
CHS
1
4
×
+
RCLA
1
4
0
5
EEX
CHS
1
0
×
-
RCLA
RCLB
×
5
3
5
9
EEX
CHS
1
5
×
-
RCLB
x²
RCLA
×
8
3
7
EEX
CHS
1
8
×
-
RCLD
×
2
0
+
CHS
RCLE
+
STOE
```

Calculate ΔSPR_T,

temperature correction

```
RCLB
1
2
2
EEX
CHS
6
×
eˣ
3
0
1
EEX
CHS
6
×
RCLA
5
4
6
9
EEX
CHS
1
1
×
+
.
0
0
7
3
-
5
9
RCLC
-
3
6
+
×
RCLE
+
PRTX
STOE
RTN
```

Best Range Program Listing

ENDURANCE OPTIMIZATION PROGRAM EQUATIONS

Optimal Altitude

$$ALT_{OPT} = 38138. - .81875\ GW$$

Optimal Rotor RPM

$$N_{R_{OPT}} = \text{Minimum of } (40.23 + .001649\ ALT + .001275\ GW)$$
$$\text{or } (98.5 + .509 \times 10^{-4}\ ALT + .5146 \times 10^{-4}\ GW + .1929 \times 10^{-8}\ ALT\ GW)$$
$$+ (T - 15.) \times .1944$$

Optimal Airspeed

$$A/S_{OPT} = \text{Minimum of } (37.7 + .001475\ ALT + .001094\ GW)$$
$$\text{or } (80.43 + .387 \times 10^{-3}\ ALT + .261 \times 10^{-3}\ GW - .4537 \times 10^{-8}\ ALT\ GW)$$
$$+ (T - 15.) \times .18$$

Uncorrected Fuel Flow

$$FF_0 = 469.6 - .0267\ ALT - .1603 \times 10^{-5}\ ALT^2 + .02956\ GW + .2183 \times 10^{-6}\ ALT\ GW + .88 \times 10^{-10}\ ALT^2\ GW$$

Temperature Correction

$$\Delta FF_T = \left(\frac{T + 5}{20}\right) \times [-2.193 - .002384\ ALT - .2754 \times 10^{-6}\ ALT^2 + .001804\ GW + .2597 \times 10^{-7}\ ALT\ GW + .1619 \times 10^{-10}\ ALT^2\ GW]$$

Best Endurance Fuel Flow

$$FF = FF_0 + \Delta FF_T$$

ENDURANCE OPTIMIZATION PROGRAM STORAGE REGISTER CONTENTS

	Primary		Secondary		
0	$-.1603\times10^{-5}$	10	$.2612\times10^{-3}$	A	GW
1	$.8797\times10^{-10}$	11	$-.4537\times10^{-8}$	B	T
2	$-.2754\times10^{-6}$	12	469.6	C	ALT
3	$.1619\times10^{-10}$	13	-.02668	D	Intermediate Values
4	98.5	14	.02956	E	FF
5	$.509\times10^{-4}$	15	$.2783\times10^{-6}$	I	
6	$.5146\times10^{-4}$	16	-2.193		
7	$.1929\times10^{-8}$	17	-.002384		
8	80.43	18	.001804		
9	$.3869\times10^{-3}$	19	$.2597\times10^{-7}$		

TABLE OF CONTENTS

Store and print input

```
*LBLA
STOA
PRTX
```

Calculate optimal altitude

```
3
8
1
3
8
RCLA
.
8
1
9
x
-
RTN
```

```
*LBLB
PRTX
STOC
```

Calculate T_{STD}

```
.
0
0
1
9
8
x
CHS
1
5
+
RTN
```

```
*LBLb
STOB
PRTX
RTN
```

Calculate optimal N_R

```
*LBLC
4
0
.
2
RCLC
.
0
0
1
6
5
x
+
RCLA
1
0
0
1
2
7
5
x
+
STOD
4
GSB1
RCLD
X>Y?
R↓
RCLB
1
5
-
.
1
9
4
4
x
+
PRTX
RTN
```

Calculate optimal TAS

```
*LBLD
3
7
.
7
RCLC
.
0
0
1
4
8
x
+
RCLA
.
0
0
1
0
9
x
+
STOE
8
GSB1
RCLE
X>Y?
R↓
RCLB
1
5
-
.
1
8
x
+
PRTX
```

Convert TAS to IAS

```
STOD
1
RCLC
1
4
5
3
6
6
÷
-
5
.
2
6
Y^x
1
5
ENT↑
2
7
3
.
2
+
LSTX
RCLB
+
÷
x
√X
RCLD
x
8
-
.
9
1
4
+
PRTX
RTN
```

Calculate and print optimal fuel flow

```
*LBLE
1
2
GSB1
RCLC
X²
STOD
RCL0
x
+
RCLD
RCLA
x
RCL1
x
+
STOE
1
6
GSB1
RCLD
RCL2
x
+
RCLD
RCLA
x
RCL3
x
+
RCLB
5
+
2
0
+
x
RCLE
+
PRTX
1/X
PRTX
RTN
```

Polynomial evaluation subroutine

SUM = A + Bx + Cy + Dxy

x = Altitude

y = Gross Weight

```
*LBL1
STOI
R↓
RCLi
ISZI
RCLi
RCLC
x
+
ISZI
RCLi
RCLA
x
+
ISZI
RCLi
RCLA
x
RCLC
x
+
RTN
```

Endurance Optimization Program Listing

MAXIMUM SPEED PROGRAM EQUATIONS

Power Limited Velocity

$$V_{MAX_{power}} = [(474.65 - 2.611\ N_R) + (-.00534 + .42\text{x}10^{-4}\ N_R) \text{ x } GW]$$

$$+ ALT \text{ x } [(.31e^{-.05135N_R}) + (-.635\text{x}10^{-5} + .1234\text{x}10^{-6}N_R - .6044\text{x}10^{-9}\ N_R^2) \text{ x } GW]$$

$$+ ALT^2 \text{ x } [\ \underbrace{(-.3176\text{x}10^{-3} + .2727\text{x}10^{-5}\ N_R - .1335\text{x}10^{-7}\ N_R^2)} +$$

$$(\underset{N_R < 100}{-.18196 + .000778\ N_R} \text{ or } \underset{N_R \geq 100}{-.10416}) \text{ x } (\qquad\qquad) \text{ x } \ln(GW)]$$

$$+\ 1.8\text{x}(T-T_{STD}) \text{ x } \left[(.44\text{x}10^{-4}\ e^{.08512\ N_R}) + (-.1758\text{x}10^{-3} + .3611\text{x}10^{-4}\ \ln(N_R)) \text{ x } GW\right]$$

$$+\ 1.8\text{x}(T-T_{STD})^{\ 2} \text{ x } \left[-.002\ e^{(-.3282\text{x}10^{-2}+65\text{x}10^{-4}N_R-.3197\text{x}10^{-6}N_R^2)\text{x}GW}\right]$$

Red-line Velocity

$$V_{MAX_{red}} = 170 \text{ kts (CAS)}$$

Stall Limited Velocity

$$V_{stall} = \frac{1}{1.687}\left[\Omega R - 42.75 \left(\frac{GW}{469.3}\right)^{1/2} \text{ x } \left(\frac{\rho_o}{\rho}\right)^{1/2}\right]$$

MAXIMUM SPEED PROGRAM STORAGE REGISTER CONTENTS

Primary		Secondary			
0	V_{MAX}'S	10	-.00534	A	GW
1	-145366.0514	11	$-.6044\times10^{-9}$	B	ALT
2	272.914286	12	$.1234\times10^{-6}$	C	$1.8\ (T-T_{STD})$
3	T	13	$-.6351\times10^{-5}$	D	N_R
4	469.08512	14	$-.1342\times10^{-7}$	E	170.003566
5	T_{STD}	15	$.2742\times10^{-5}$	I	
6	$(\frac{P}{Po})^{1/2}$	16	$-.1384\times10^{-3}$		
7	-2.611	17	$-.3197\times10^{-6}$		
8	474.65	18	$.6499\times10^{-4}$		
9	$.42\times10^{-4}$	19	-.003282		

```
*LBLA
STOA      Store and print inputs
PRTX
RTN
*LBLB
STOB
PRTX
RCLE      Calculate T_STD
FRC
x
CHS
1
5
+
STO5
RTN
*LBLC
STO3
PRTX
RTN
*LBLD
STOD
PRTX
RTN
*LBL1
RCLD      Polynomial evaluation
x^2       subroutine
RCL i
x         SUM = A + Bx (+C x^2)
ISZI
*LBL2     x = N_R
RCLD
RCL i
x
+
ISZI
RCL i
+
ISZI
RTN
*LBLE
RCL3      Calculate power
RCL5
-         limited velocity
1
.
8
x
STOC
7
STOI
0
GSB2
STO0
0
GSB2
RCLA
x
ST+0
GSB1
RCLA
x
RCL1
FRC
RCLD
x
e^x
.
3
1
x
+
RCLB
x
ST+0
GSB1
ENT↑
ENT↑
RCLD
EEX
2
X≠Y?
X⇄Y
R↓
7
7
8
CHS
EEX
CHS
6
x
.
1
8
1
9
6
+
x
RCLA
LN
x
-
RCLB
x^2
x
ST+0
GSB1
RCLA
x
e^x
.
0
0
2
x
RCLC
x^2
x
ST-0
RCLD
LN
3
6
EEX
CHS
6
x
1
7
6
EEX
CHS
6
-
RCLA
x
RCL4
FRC
RCLD
x
e^x
4
4
EEX
CHS
6
x
+
RCLC
x
ST+0
1
RCLB      Calculate sqrt(σ/σ_o)
RCL1
+
÷
5
.
2
5
6
y^x
1
5
RCL2
÷
LSTX
RCL3
+
÷
x
√x
STO6
1/x
RCLA      Calculate stall
RCL4
÷         limited velocity
√x
x
4
2
.
7
5
x
CHS
RCLD
7
x
+
1
.
6
8
7
+
RCL0
X⇄Y
X≠Y?
STO0
RCLE
INT       Calculate redline velocity
RCL6
1/x
x
RCL0
X⇄Y
X≠Y?
STO0
RCL0
PRTX      Convert TAS to IAS
RCL6
x
8
-
RCL2
FRC
÷
PRTX
RTN
```

Maximum Speed Program Listing

MINIMUM TAKEOFF NOISE PROGRAM EQUATIONS

Uncorrected Optimal Rate of Climb

$$ROC_{uncor} = 4628. - .06677\ GW + .03441\ ALT - .3119\times10^{-5}\ GW\ ALT - .1311\times10^{-9}\ GW\ ALT^2$$

Temperature Corrected Rate of Climb

$$ROC = ROC_{uncor} - 29.08\ (T\ (°C) - 30.) + .003263 \times ROC_{uncor} \times (T\ (°C) - 30.)$$

Climb Angle

$$\gamma = TAN^{-1}\left(\frac{ROC\ (fpm)}{TAS\ (fpm)}\right) \quad \text{where } TAS = 95 \text{ kts} = 9615.9 \text{ fpm}$$

Effective Perceived Noise Level

$$EPNL = 88.58 - 2.369\ \gamma + .1249\ \gamma^2 - .002684\ \gamma^3 + 1.862\times10^{-4}\ GW + 16.667\ M_t$$

MINIMUM TAKEOFF NOISE PROGRAM STORAGE REGISTER CONTENTS

	Primary		Secondary		
0	-.06677	10	0.0	A	GW
1	.03441	11		B	ALT
2	$-.3119\times10^{-5}$	12		C	T
3	.003263	13		D	ROC
4	459.7	14		E	N_R
5	145366.	15		I	
6	9615.914286	16			
7	$.1862\times10^{-3}$	17			
8	CLIMB ANGLE	18			
9	$-.1311\times10^{-9}$	19	0.0		

```
*LBLA        Store and print inputs
STOA
PRTX
RTN
*LBLa
STOB
PRTX
RTN
*LBLB
1            Convert °C to °F
.
8
×
3
2
+
STOC
PRTX
RTN
*LBLD
SPC          Calculate rate of climb
4
6
2
8
RCL0
RCLA
×
+
RCL1
RCLB
×
+
RCL2
RCLA
×
RCLB
×
+
RCLB
x²
RCLA
×
RCL9
×
+
STOI
RCLC
3
2
−
1
.
8
÷
3
0
−
2
9
.
0
8
[illegible]
×
CHS
LSTX
RCLI
×
RCL3
×
+
RCLI
+
*LBL4
PRTX
STOD
RCL6         Calculate climb angle
÷
TAN⁻¹
STO8
RCLD
RTN
*LBLC
SPC          Print TAS - 95 knots
9
5
PRTX
1            Convert TAS to IAS
RCL8
RCL5
+
−
5
.
2
5
6
yˣ
5
9
RCL4
+
LSTX
RCLC
+
÷
×
√x
9
5
×
0
−
RCL6
FRC
÷
PRTX
RTN
*LBLE
1            Store and print N_S
0
0
*LBLe
STOE
SPC
PRTX
RCLC         Calculate N_C
RCL4
+
√x
4
9
.
0
4
×
STOI
1
6
0
.
2
7
RCLE
7
×
+
RCLI
÷
1            Calculate EPNL
6
.
6
6
7
×
8
0
.
5
8
+
RCL7
RCLA
×
+
RCL8
2
.
3
6
9
×
−
RCL8
x²
.
1
2
4
9
×
+
RCL8
3
yˣ
.
0
0
2
6
0
4
×
−
PRTX
SPC
RTN
```

Minimum Takeoff Noise Program Listing

MINIMUM LANDING NOISE PROGRAM EQUATIONS

Optimal Descent Angle

$$\gamma = 4.116 + .7205\times10^{-4}\ GW + .4821\times10^{-8}\ GW^2$$
$$- .4362\times10^{-3}\ GW\ \frac{\rho}{\rho_0} + 13.44\ \frac{\rho}{\rho_0}$$

Rate of Descent

$$ROD = TAS\ (fpm)\ TAN\ \gamma = 9615.9\ TAN\ \gamma$$

Effective Perceived Noise Level

$$EPNL = [100.84 - 2.766\ \gamma + .2955\ \gamma^2] \quad \gamma \leq 6°$$
$$[126.64 - 7.068\ \gamma + .298\ \gamma^2] \quad \gamma > 6°$$
$$+ .001955\ GW$$
$$+ [17.8\ (M_t - .74) + 376.1\ (M_t - .74)^2] \quad M_t > .74$$
$$+ 0 \quad M_t \leq .74$$

MINIMUM LANDING NOISE PROGRAM STORAGE REGISTER CONTENTS

	Primary		Secondary		
0	$\frac{\rho}{\rho o}$, GW, γ	10	0.0	A	GW
1	EPNL	11	$.4821 \times 10^{-8}$	B	ALT
2	$\frac{\rho}{\rho o}$	12	$.7205 \times 10^{-4}$	C	T
3	459.7	13	4.116	D	N_R, $(M_t - .74)$
4	9616.000196	14	.2955	E	DESCENT ANGLE
5	145365.9143	15	-2.766	I	
6	5.256	16	100.84		
7	376.1	17	.298		
8	13.44	18	-7.068		
9	$-.4362 \times 10^{-3}$	19	126.64		

```
001  *LBLA   -----------------------------
002   STOA   Store and print inputs
003   PRTX
004    RTN
005  *LBLa
006   STOB
007   PRTX
008    RTN
009  *LBLB   -----------------------------
010      1
011      .   Convert °C to °F
012      8
013      x
014      3
015      2
016      +
017   STOC   -----------------------------
018   PRTX
019    RTN
020  *LBL5   -----------------------------
021    SPC   Calculate σ/σ0
022      1
023   RCL8
024   RCL5
025      +
026      -
027   RCL6
028    Y^X
029      5
030      9
031   RCL3
032      +
033   LSTX
034   RCLC
035      +
036      +
037      x
038   STO2
039    RTN
040  *LBLD   -----------------------------
041   GSB5   Calculate descent angle
042   RCLA
043   STO0
044      1
045      1
046   GSB1
047   RCL2
048   RCL8
049      x
050      +
051   RCLA
052   RCL2
053      x
054   RCL9
055      x
056      +
057   STOE   -----------------------------
058    TAN
059   RCL4   Calculate rate of descent
060      x
061   PRTX
062    RTN
063  *LBLd   -----------------------------
064   STOI   Calculate new descent angle
065   RCL4   from given ROD
066      ÷
067 TAN^-1
068   STOE
069   RCLI
070   PRTX
071    RTN
072  *LBLC   -----------------------------
073   GSB5   Print TAS - 95 knots
074    SPC
075      9
076      5
077   PRTX   -----------------------------
078   RCL2
079    √X    Convert TAS to IAS
080      x
081      8
082      -
083   RCL5
084    FRC
085      +
086   PRTX
087    RTN
088  *LBLE   -----------------------------
089      1   Store and print N_R
090      0
091      0
092  *LBLe
093    SPC
094   STOD
095   PRTX   -----------------------------
096   RCLE
097   STO0   Calculate EPNL_0
098      6
099   X>Y?
100   GTO2
101      1
102      7
103   GTO3
104  *LBL2
105      1
106      4
107  *LBL3
108   GSB1
109   RCLA
110   RCL4
111    FRC
112      x
113      +
114   STO1   -----------------------------
115   RCLC
116   RCL3   Calculate M_t
117      +
118    √X
119      4
120      9
121      .
122      0
123      4
124      x
125   STOI
126      1
127      6
128      0
129      .
130      2
131      7
132   RCLD
133      7
134      x
135      +
136   RCLI
137      ÷   -----------------------------
138      .
139      7   Calculate M_t correction
140      4
141      -
142   STO0
143   X<0?
144   GTO4
145      1
146      7
147      .
148      8
149      x
150   RCL0
151    X^2
152   RCL7
153      x
154      +
155   RCL1
156      +
157   STO1   -----------------------------
158  *LBL4
159   RCL1   Print EPNL
160   PRTX
161    SPC
162    RTN   -----------------------------
163  *LBL1
164   STOI   Polynomial evaluation
165    R↓    subroutine
166   RCL0
167    X^2
168   RCL1
169      x   SUM = A + Bx + Cx^2
170   ISZI
171   RCL0   x = Contents of register 0
172   RCL1
173      x
174      +
175   ISZI
176   RCL1
177      +
178    RTN   -----------------------------
```

Minimum Landing Noise Program Listing

APPENDIX II. PROGRAM USER INSTRUCTIONS

This Appendix is a user's guide for the mission optimization programs. It contains general instructions for loading the programs into the HP-97 via the magnetic cards, and specific instructions for exercising each of the eight programs. A list of card symbols and units is included.

The optimization programs can be used by referring to this Appendix alone. It is recommended, however, that the user review the body of this report to become familiar with the background, technical approach, and assumptions. The HP-97 manufacturer's manual should also be studied before using the computer.

GENERAL INSTRUCTIONS FOR LOADING HP-97 PROGRAMS

1. Select the desired program card and associated data card from the card holder.

2. Ensure that the PRGM-RUN switch is set to RUN. PRGM RUN

3. Set the Print Mode switch to MAN. MAN TRACE NORM

4. Slowly insert side one of the program card, printed side up, into the card reader slot on the front left of the calculator. When the card is about half way into the slot, a motor engages and draws the card through the calculator and out the back. Let the card slide freely.

5. The calculator display should read $\boxed{\text{CRD}}$ to prompt you that side 2 of the card must be read in.

6. Now pass side 2 of the card through the calculator, again face up.

7. If after either pass of the card through the card reader, the display shows $\boxed{\text{ERROR}}$, that side of the card did not read properly. Press $\boxed{\text{CLX}}$, then pass that side of the card through the card reader again.

8. When both sides of the card have been read properly, insert the program card into the window slot above the left register. The markings on the card should be directly over the keys marked $\boxed{\text{A}}$ $\boxed{\text{B}}$ $\boxed{\text{C}}$ $\boxed{\text{D}}$ $\boxed{\text{E}}$. The markings on the card now identify the function of each of these five keys.

9. To load the data card, repeat steps 4, 5, and 6.

10. You are now ready to use the program.

Card Symbols and Units

ALT	Pressure altitude, feet
A/S	Airspeed, knots
EPNL	Effective perceived noise level, dB
FF	Total fuel flow, pounds per hour
GW	Gross weight, pounds
H WIND	Headwind speed, knots (negative for tailwind)
IAS	Indicated airspeed, knots
NE	Number of engines operating
NR	Rotor speed, percent (100% = 185 rpm)
OPT	Optimum
Q	Engine output torque, percent (100% = 3200 SHP per engine at 100% N_R)
ROC	Rate of climb, feet per minute
ROD	Rate of descent, feet per minute
SHP	Total engine shaft horsepower
SPE	Specific endurance, hours per pound of fuel
SPR	Specific range, nautical miles per pound of fuel
STD	International standard atmosphere (ISA)
T	Outside ambient temperature, °C or °F as specified
TAS	True airspeed, knots
Vmax	Maximum airspeed, knots

Program A: Power Required

This program calculates total power required for steady state level flight and specified gross weight, airspeed, rotor rpm, pressure altitude, and temperature.

1. Key in gross weight in pounds, press [A]. The input is printed.

2. Key in pressure altitude in feet, press [B]. The input is printed.

3. Key in outside ambient temperature. If in degrees Fahrenheit, press [C]; if in degrees Centigrade, press [f][C]. Degrees Fahrenheit is printed.

4. Key in percent rpm, press [D]. The input is printed.

5. Key in airspeed in knots. If true airspeed, press [E]; if indicated airspeed, press [f][E]. True airspeed is printed.

6. Press [f][A]. Power required is printed, and then percent torque is displayed and printed.

Program B: Fuel Flow

This program calculates total fuel flow for specified power required or NR/torque combination, pressure altitude, temperature, airspeed, and number of operating engines.

1. If available, key in total horsepower, press [A] . The input is printed. Or, key in NR, press [ENTER↑], then key in Q, press [f] [A]. The inputs are printed, then total horsepower is calculated and printed.

2. Key in pressure altitude in feet, press [B] . The input is printed.

3. Key in outside ambient temperature. If in degrees Fahrenheit, press [C] ; if in degrees Centigrade, press [f] [C]. Degrees Fahrenheit is printed.

4. Key in airspeed in knots. If true airspeed, press [D] . If indicated airspeed, press [f] [D] . True airspeed is printed.

5. Key in number of operating engines, press [E]. The input is printed.

6. Press [f] [E] . Total fuel flow in pounds/hour is displayed and printed.

Program C: Best Range Conditions

This program calculates the cruise flight conditions that result in maximum specific range (nautical miles per pound of fuel) for specified gross weight, temperature, and headwind.

1. Key in gross weight in pounds, press $\boxed{A}$. The input is printed. The optimal pressure altitude in feet is automatically calculated and displayed.

2. If the optimal altitude displayed is accepted, press $\boxed{B}$. If a different altitude is desired, key it in first (in feet) and then press $\boxed{B}$. The input is printed. The ISA temperature in degrees Centigrade at the input altitude is automatically calculated and displayed.

3. If the ISA temperature displayed is accepted, press $\boxed{f}\boxed{B}$. If a different temperature is desired, key it in first (in degrees Centigrade) and then press $\boxed{f}\boxed{B}$. The input is printed.

4. Key in headwind (+) or tailwind (-) in knots, press $\boxed{C}$. The input is printed.

5. Press $\boxed{D}$. Optimal percent rotor rpm is displayed and printed.

6. Press $\boxed{E}$. Optimal airspeed in knots, true followed by indicated, is displayed and printed.

Program D: Best Range

This program calculates the best achievable specific range(nautical miles per pound of fuel) for conditions of optimal airspeed and rotor rpm as defined by Program C and specified gross weight, altitude, temperature, and headwind.

1. Key in gross weight in pounds, press [A] . The input is printed.

2. Key in pressure altitude in feet, press [B] . The input is printed.

3. Key in temperature in degrees Centigrade, press [C] . The input is printed.

4. Key in headwind (+) or tailwind (-) in knots, press [D] . The input is printed.

5. Press [E] . Best specific range in nautical miles per pound of fuel is displayed and printed.

NOTE: With the specific range displayed in the last step, actual range available can be quickly calculated by inputing fuel remaining and multiplying.

Program E: Best Endurance

This program calculates the best achievable specific endurance (hours per pound of fuel) and the associated optimal cruise flight conditions for specified gross weight and temperature.

1. Key in gross weight in pounds, press $\boxed{A}$. The input is printed. The optimal pressure altitude in feet is automatically calculated and displayed.

2. If the optimal altitude displayed is accepted, press $\boxed{B}$. If a different altitude is desired, key it in first (in feet) and then press $\boxed{B}$. The input is printed. The ISA temperature in degrees Centigrade at the input altitude is automatically calculated and displayed.

3. If the ISA temperature displayed is accepted, press $\boxed{f}\boxed{B}$. If a different temperature is desired, key it in first (in degrees Centigrade) and then press $\boxed{f}\boxed{B}$. The input is printed.

4. Press $\boxed{C}$. Optimal percent rotor rpm is displayed and printed.

5. Press $\boxed{D}$. Optimal airspeed in knots, true followed by indicated, is displayed and printed.

6. Press $\boxed{E}$. Fuel flow in pounds/hour and specific endurance in hours/pound of fuel are successively displayed and printed.

NOTE: With the specific endurance displayed in the last step, actual endurance available can be quickly calculated by inputing fuel remaining and multiplying.

Program F: Maximum Speed

This program calculates maximum sustained level flight airspeed as limited by power, stall, or structure for specified gross weight, altitude, temperature, and percent rotor rpm.

1. Key in gross weight in pounds, press [A]. The input is printed.

2. Key in pressure altitude in feet, press [B]. The input is printed. The ISA temperature in degrees Centigrade at the input altitude is automatically calculated and displayed.

3. If the ISA temperature displayed is accepted, press [C]. If a different temperature is desired, key it in first (in degrees Centigrade) and then press [C]. The input is printed.

4. Key in percent rotor rpm, press [D]. The input is printed.

5. Press [E]. Maximum airspeed in knots, true followed by indicated, is displayed and printed.

Program G: Minimum Takeoff Noise

This program calculates the optimum rate of climb for minimizing ground observed noise. Climb airspeed is 95 knots true; the corresponding indicated airspeed is calculated for the specified ambients. Rotor speed is 100% N_R. EPNL noise level can also be calculated for specified rate of climb and N_R.

1. Key in gross weight in pounds, press $\boxed{A}$. The input is printed.

2. Key in pressure altitude in feet, press $\boxed{f}\boxed{A}$. The input is printed.

3. Key in temperature in degrees Centigrade, press $\boxed{B}$. The input is printed.

4. Press $\boxed{C}$. Optimal airspeed in knots, true followed by indicated, is displayed and printed.

5. Press $\boxed{D}$. Optimal rate of climb in feet/minute is displayed and printed.

6. If a different rate of climb is desired, key it in (in fpm) and press $\boxed{f}\boxed{D}$. The input is printed.

7. Press $\boxed{E}$. Rotor rpm (100%), then noise in EPNL dB are displayed and printed.

8. If a rotor rpm other than 100 percent is desired, key it in and press $\boxed{f}\boxed{E}$. The input followed by the associated EPNL in dB is displayed and printed.

Program H: Minimum Landing Noise

This program calculates the optimum autorotative rate of descent for minimizing ground observed noise. Descent airspeed is 95 knots true; the corresponding indicated airspeed is calculated for the specified ambients. Rotor speed is 100% N_R. EPNL noise level can also be calculated for specified rate of descent and N_R.

1. Key in gross weight in pounds, press [A] . The input is printed.

2. Key in pressure altitude in feet, press [f][A] . The input is printed.

3. Key in temperature in degrees Centigrade, press [B] . The input is printed.

4. Press [C] . Optimal airspeed in knots, true followed by indicated, is displayed and printed.

5. Press [D] . Optimal rate of descent in feet/minute is displayed and printed.

6. If a different rate of descent is desired, key it in (in fpm) and press [f][D] . The input is printed.

7. Press [E] . Rotor rpm (100%), then noise in EPNL dB are displayed and printed.

8. If a rotor rpm other than 100 percent is desired, key it in and press [f][E] . The input followed by the associated EPNL in dB is displayed and printed.

APPENDIX III. IMPACT OF CURRENT CH-53 FLIGHT RESTRICTIONS

The performance optimization programs developed under this contract define optimum altitude, airspeed, and rotor rpm without regard to flight envelope restrictions that may change or that may not apply in selected situations. As a result, applicable CH-53 flight restrictions must be superimposed on the theoretical optimums, and otherwise achievable performance may be somewhat degraded, particularly at extremes of weight and altitude. Flight demonstration of performance optimization should not be attempted for conditions outside the allowable operating envelope as defined in the appropriate Flight Manual, or as dictated by local operating conditions.

The current CH-53A/D NATOPS Flight Manual defines normal rotor rpm range as 95 to 105 percent. Theoretically optimum rotor rpm's less than 95 percent, which occur at light weights and low altitudes, and particularly for maximum endurance, cannot, therefore, be used. The result is about a one percent reduction in theoretically achievable range and an 8 percent reduction in theoretically achievable endurance. At normally heavier gross weights, the low rpm limitation has no impact.

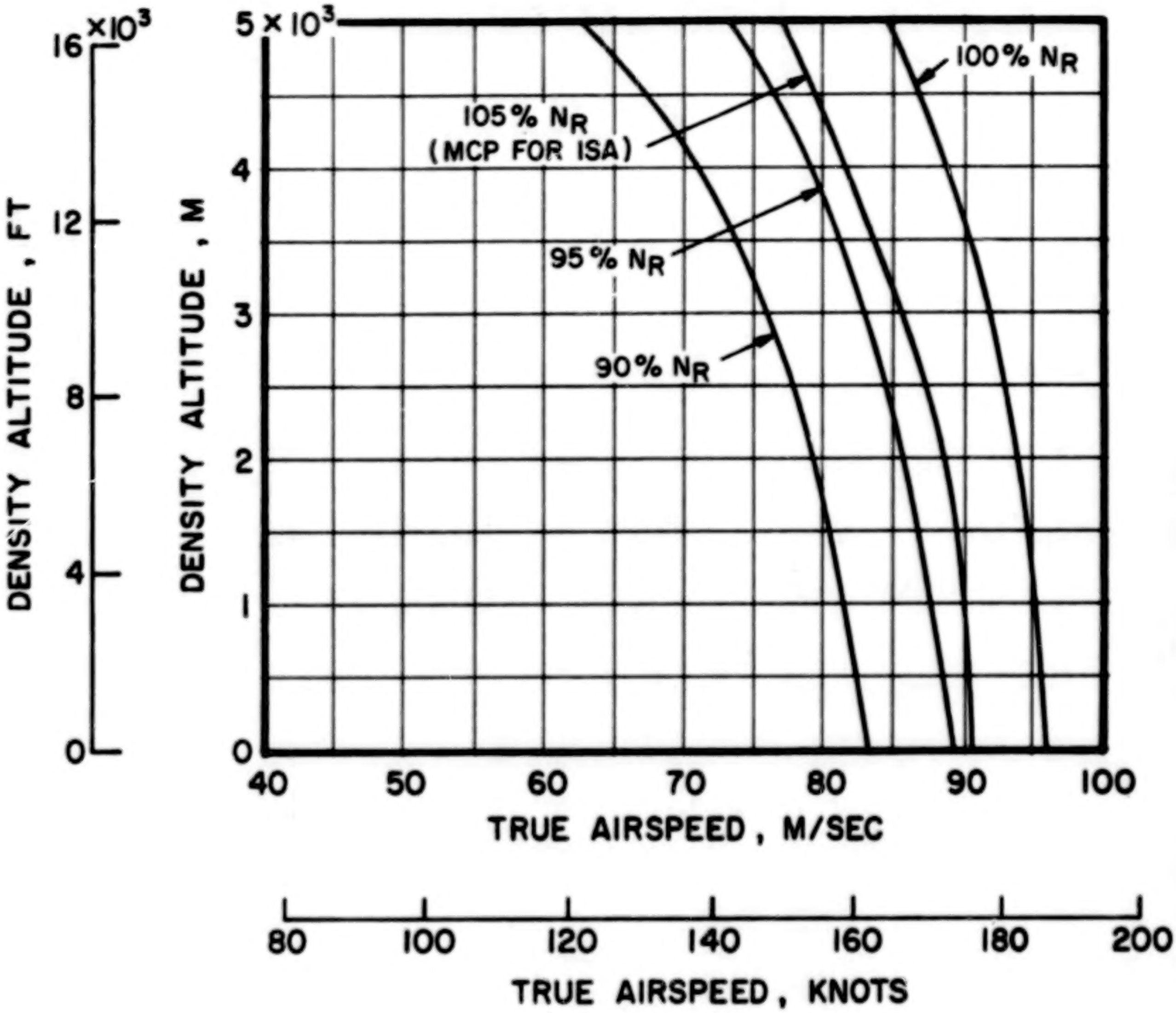
Acceptable combinations of airspeed and rotor rpm can also be constrained by the ability to achieve successful entry into autorotation following loss of power. Rotor rpm must be high enough, and airspeed low enough, to prevent unacceptable rpm decay during the time it takes the pilot to react and to take corrective action. Excessive rpm decay can result in high flapping, degraded handling qualities, and the possibility of reaching the windmill brake state in which increasing rate of descent begins to retard rather than to accelerate rotor speed.

The most extreme (but highly unlikely) autorotative entry situation occurs following simultaneous, instantaneous loss of power from both engines at high cruise speed. The behavior of the helicopter and the rotor following abrupt power loss is very complex, and depends on initial trim conditions, pilot reaction time, and the precise corrective action taken. Analytical treatment is difficult, but semi-empirical methods using flight simulation techniques have made it possible to estimate boundary flight envelopes of gross weight, density altitude, airspeed, and rotor rpm for this situation. These envelopes are shown in Figure 33.

The impact of the low rotor rpm and autorotative entry constraints on range and endurance is summarized in Figures 34 and 35 respectively. The low rpm constraint degrades both range and endurance at combinations of light weight and low altitude. The autorotative entry criterion degrades both range and endurance at combinations of heavy weight and high altitude. For typical weights and altitudes, there is no appreciable degradation since the optimum flight parameters are within the operational flight envelope.

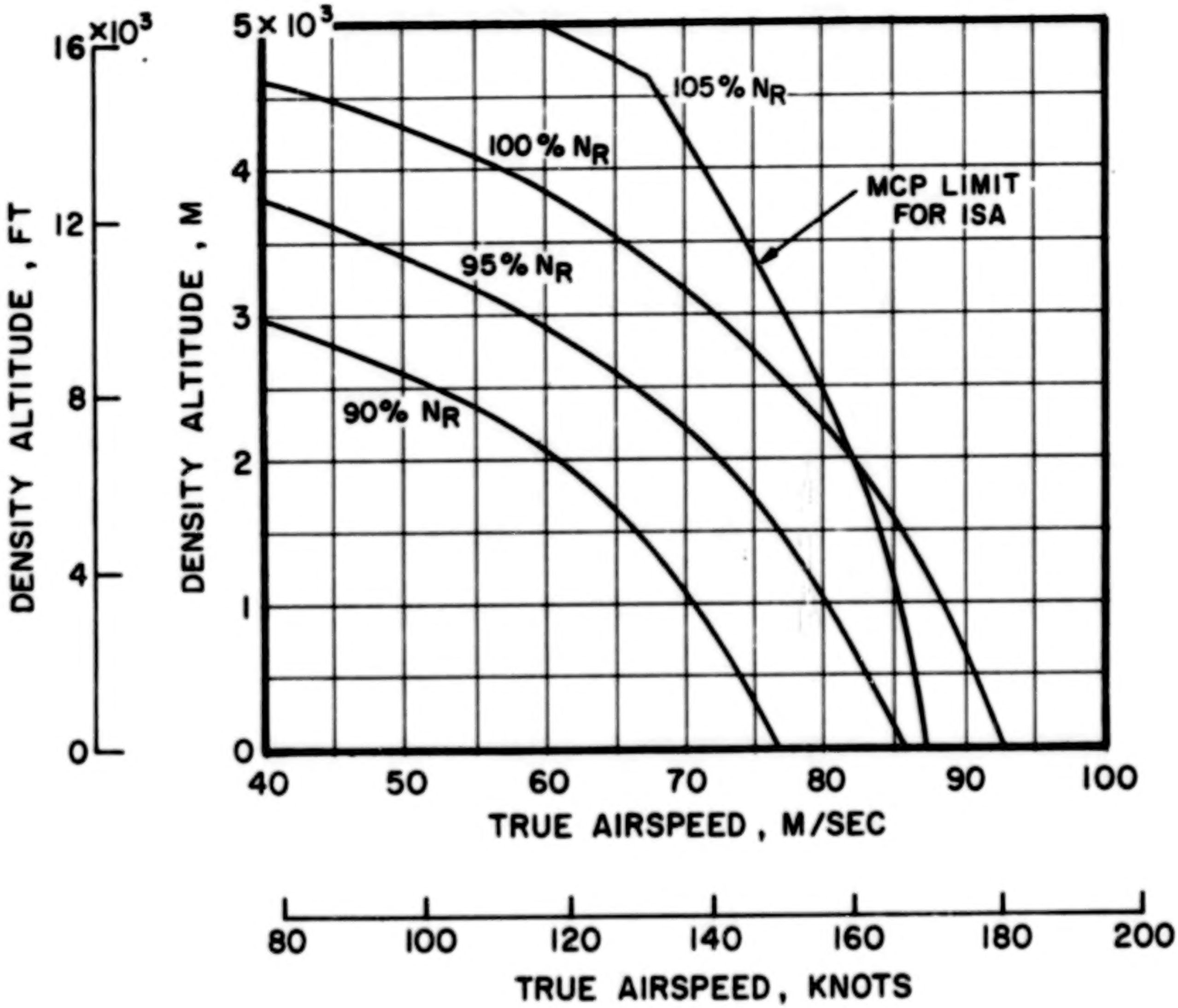
The impact of the autorotative entry criterion on maximum cruise speed is shown in Figure 36 for 100 percent rotor rpm. The apparent penalty at heavy gross weights is significant; however, increased rotor rpm can be used to recover much of the speed degradation (see Figure 33).

Takeoff and landing noise minimization is generally unaffected by flight envelope restrictions since altitudes and airspeeds are relatively low. Optimum climb and descent are defined at a nominal rotor rpm of 100 percent. Should a higher rpm be desired to provide additional recovery margin in the event of power loss or flight path misjudgement, the noise penalty is only about one dB EPNL.



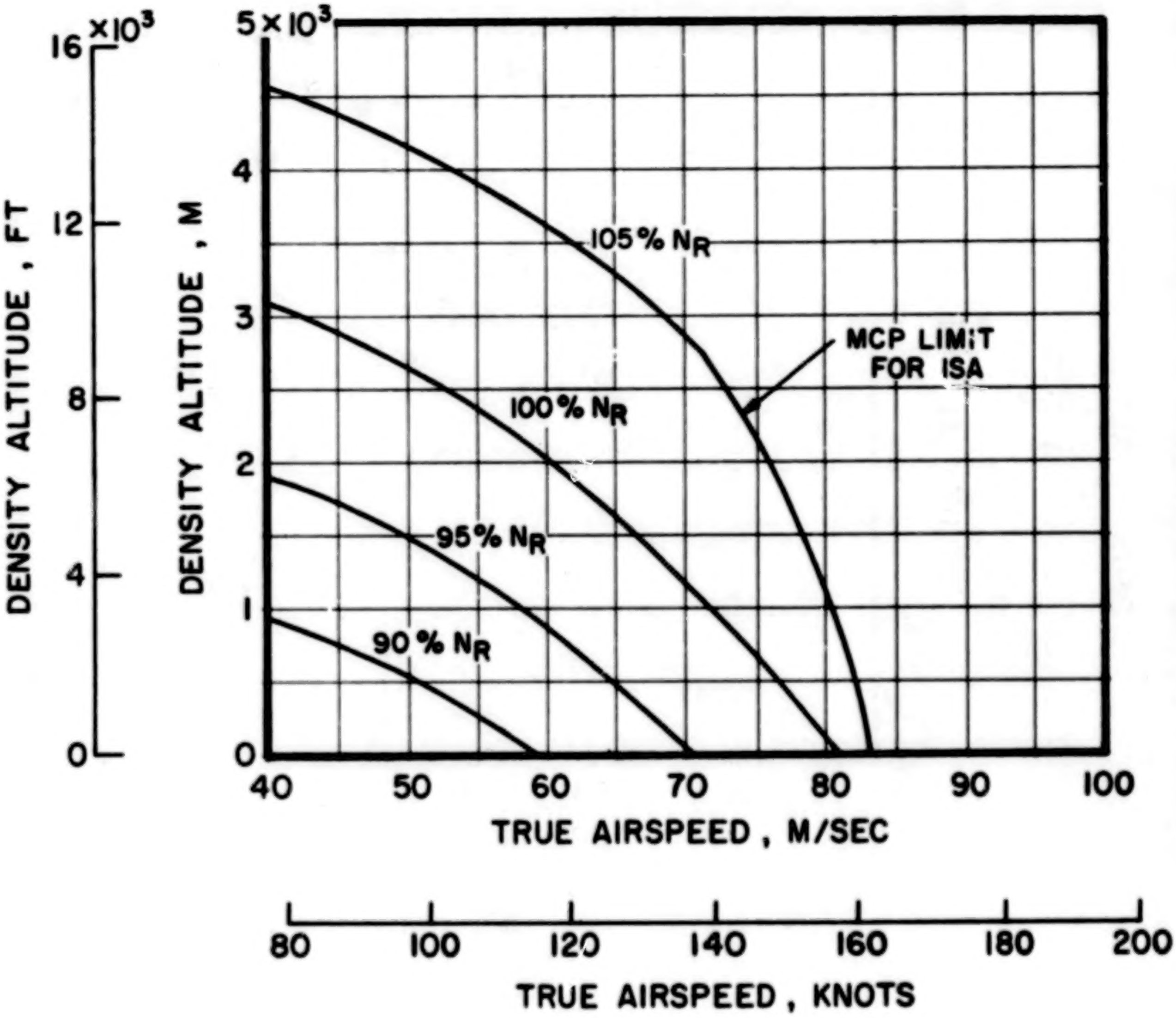
(a) GW = 11790 kg (26000 lb)

Figure 33. Airspeed Limitations to Permit Entry Into Autorotation Following Abrupt Total Power Loss - Estimated.



(b) GW = 15420 kg (34000 lb)

Figure 33. - Continued.



(c) GW = 19050 kg (42000 lb)

Figure 33. - Concluded.

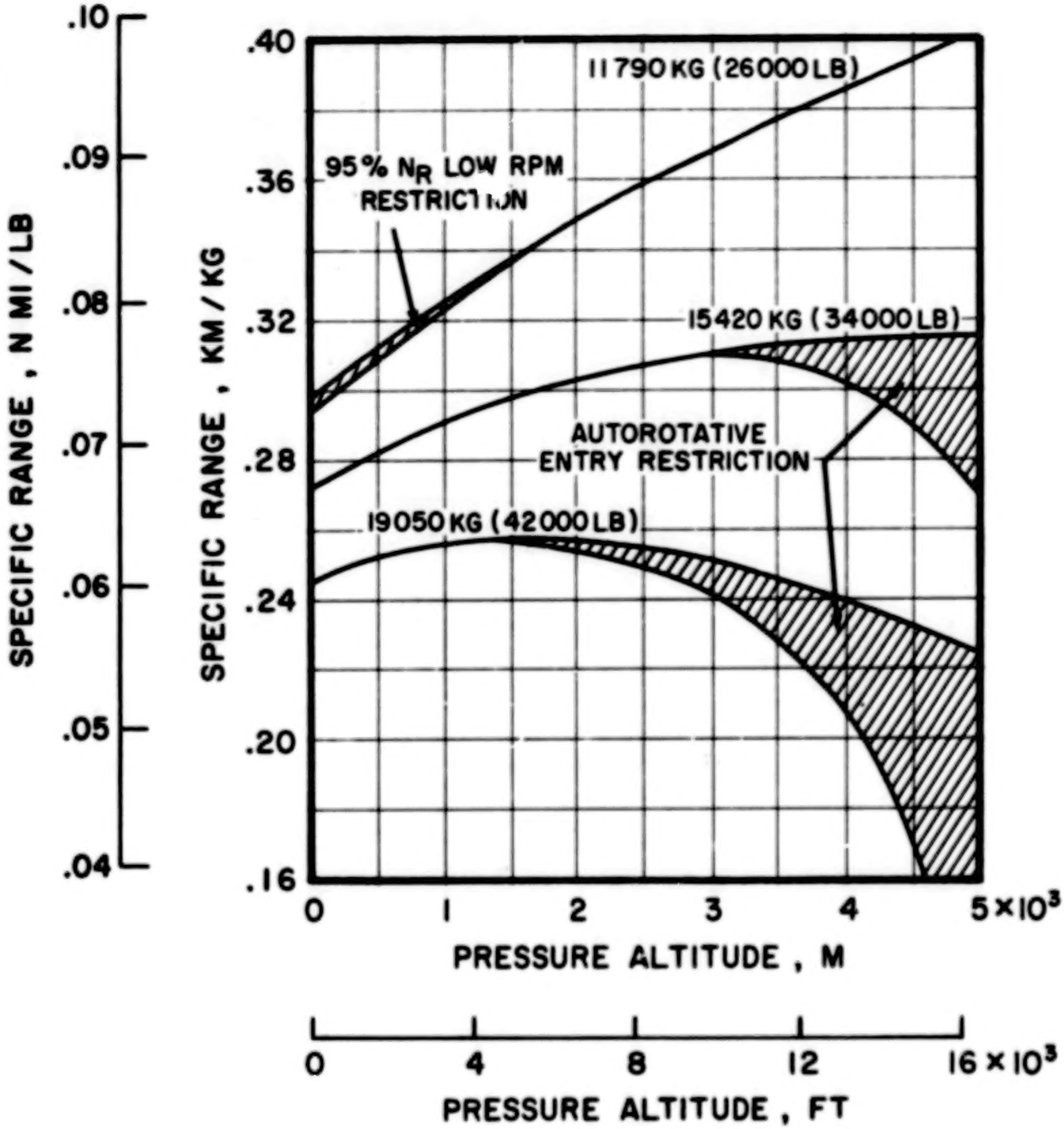


Figure 34. Flight Restriction Impact on Best Specific Range for ISA and Zero Headwind.

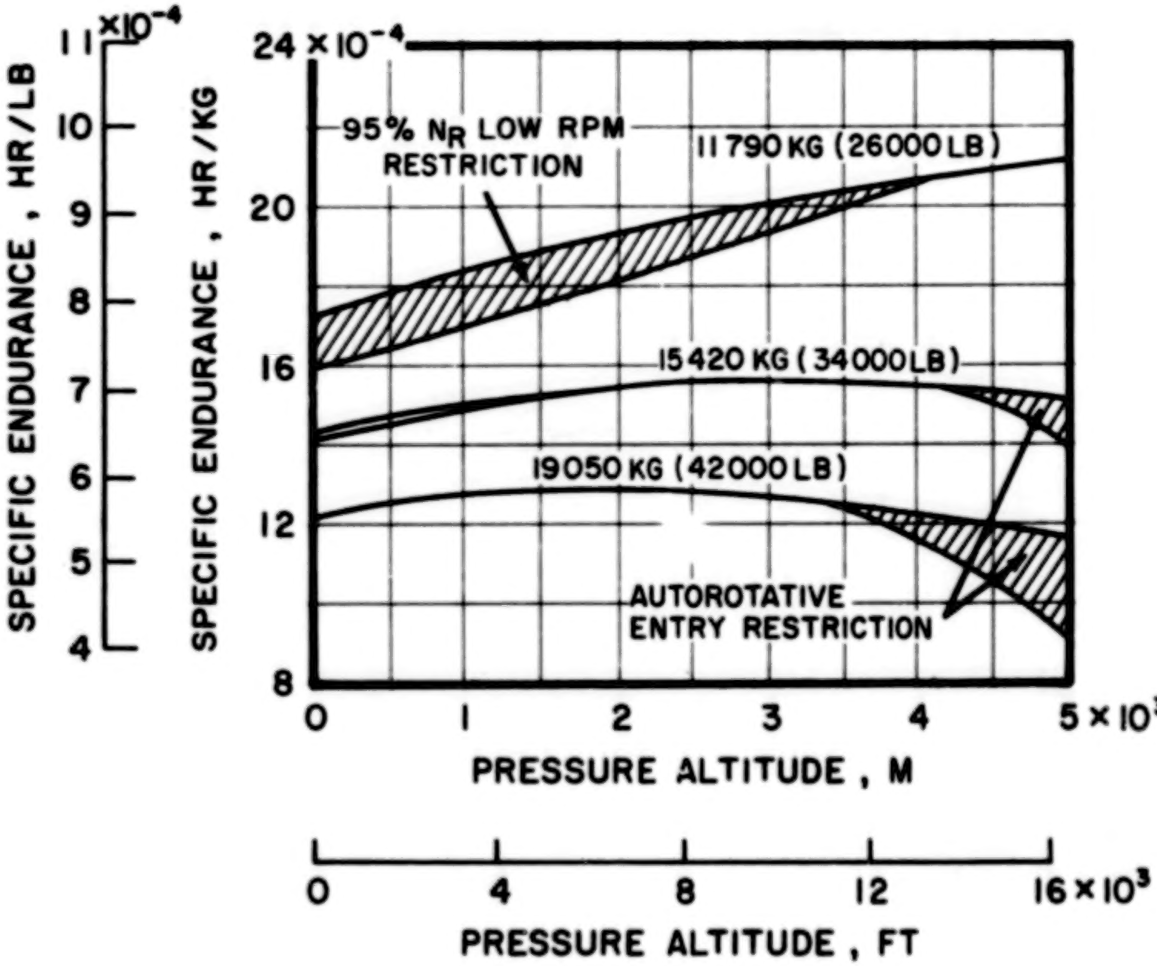


Figure 35. Flight Restriction Impact on Best Specific Endurance for ISA.

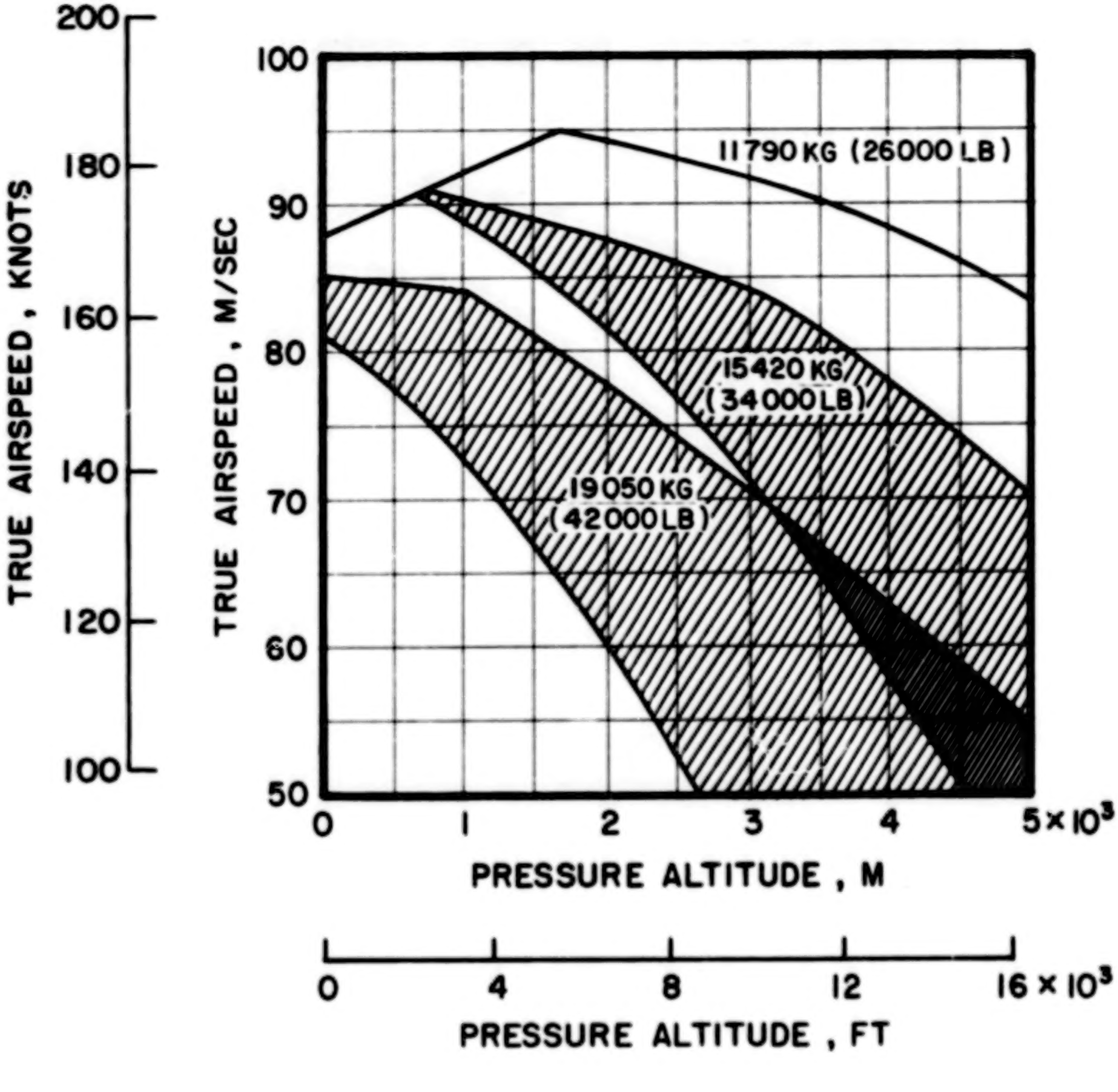


Figure 36. Flight Restriction Impact on Maximum Sustained Airspeed (100% rpm, ISA).

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Final Report

16. Abstract

The Helicopter Mission Optimization Study described in this report is a part of the NASA Civil Helicopter Technology Program. Its objective is to demonstrate the feasibility of using low-cost, portable computer technology to help a helicopter pilot optimize flight parameters to minimize fuel consumption and takeoff and landing noise. Eight separate computer programs have been developed for use in the helicopter cockpit using the Hewlett Packard HP-97 or HP-67 hand-held computer. The programs provide the helicopter pilot with the ability to calculate power required, minimum fuel consumption for both range and endurance, maximum speed and a minimum noise profile for both takeoff and landing. Each program is defined by a maximum of two magnetic cards. The helicopter pilot is required to key in the proper input parameter such as gross weight outside air temperature or pressure altitude and the desired output is designated and, in the case of the HP-97, printed on paper tape for future reference.

The computer programs developed in this study demonstrate the feasibility of a cockpit computer approach to flight optimization. However, the inherent limitations of the HP-97 and HP-67 make some of the required pilot manipulations more cumbersome than may be acceptable in a production system. These limitations will largely disappear with the availability of fast-developing small computer technology.

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